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SAFETY ANALYSIS OF RADIONUCLIDE RELEASE TO THE CLINCH RIVER

Supplement No. 3 to Status Report No. 5 on Clinch River Study

By

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INTRODUCTION

When radioactive material is released to a body of water, there is a complex network of mechanisms by which the material can be transmitted from one component, animate or inanimate, to another. At each point in the network or chain of transmission, human or other life forms may be subject to some degrees of radiation exposure.

The probability of human exposure and the degree of exposure depend upon many interrelated factors. These include: (1) the adequacy of control measures to keep the levels of contamination within safe limits; (2) the sources, types, quantities, and distribution of radioactive contaminants released to the water; (3) the physical, chemical and biological conditions in the body of water; (4) the use of water for drinking, domestic, and industrial purposes; and (5) the number of people exposed and their habits which may influence the nature and extent of exposure. Definitive information about these and other pertinent factors is necessary for realistic estimates of the potential exposures and evaluation of their significance.

In the Clinch River Study, safety evaluation depends primarily upon descriptive and analytical data needed to define exposure factors. Criteria of permissible radiation exposures, adopted by the International Commission on Radiological Protection (ICRP), the Federal Radiation Council (FRC), and the National Committee on Radiation Protection and Measurements (NCRP), are accepted as guides.[1-5] The MPC_w values employed to assess radiation dose to man follow the recommendations of ICRP found in Publication 2 and Publication 6. In Publication 6 the ICRP recommended an increase in the MPC_w values of ^{90}Sr when the skeleton and total body are the organs of reference, and they are used accordingly. On these bases, estimates of human exposure that may result from Clinch-Tennessee River contamination are made and conclusions reached regarding their importance.

Objectives of Study

The immediate objective is to evaluate the potential contribution of each relevant pathway in causing radiation exposure to man. The most direct means of evaluating internal exposures is to determine the amounts of radioactive material in the bodies of exposed members of population groups; for example, by whole-body counting or excretion analyses. The quantity of ^{137}Cs in the total body of eleven employees of the Oak Ridge Gaseous Diffusion Plant was measured by whole-body counting.[6] All were known to drink treated water from the Clinch River during working hours. Results were inconclusive, however, because the amount of ^{137}Cs in other parts of the diet due to fallout from weapons tests precluded an estimate of the proportion of the measured body burden that was attributable to consumption of Clinch River water. Therefore, exposures were calculated from measurements of the amounts of radioactive material in the various environmental media, with assumptions as to the fraction of this material that may affect the exposed population.

The long-range objectives are evaluation of the total potential of radioactivity in this river environment in causing exposures and delineation of exposure pathways so as to estimate the prevailing levels of safety and understand the potential for exposure of each such pathway in the future. The study is also directed toward establishment of parameters that affect downstream exposure from river disposal under many combinations of conditions.

Limitations of Analysis

Although human or other life forms may receive some degree of radiation exposure, this study does not consider effects upon biota in general but rather confines its efforts to estimation of radiation doses to man. The critical population groups may be identified from information about the critical radionuclides and principal exposure pathways, and with knowledge of the population distribution and habits. Not all of the desired information is available. For example, in order to complete some calculations, it is necessary to estimate the dietary habits and amounts of principal food-stuffs consumed as well as occupational and recreational habits. It is also desirable to confirm several estimates of external radiation which were calculated from measured concentrations of radionuclides in environmental media.

RADIONUCLIDES RELEASED AND CONCENTRATIONS IN THE RIVERS

Virtually all radioactive materials emanating from the Laboratory and reaching the Clinch River passes through White Oak Creek. The final control point for waste water released to the river at Clinch River Mile (CRM) 20.8 is at White Oak Dam(Fig. 1).

Discharges from White Oak Creek to Clinch River

The flow of water through White Oak Dam has been determined by several methods.[7,8] During the period 1953-1955, while White Oak Lake was still impounded, a gaging station at the dam was used. After 1955, when the lake was drained and the gaging station inactivated, flow was calculated by summing the separate measurements of flow in White Oak Creek and Melton Branch which are the principal surface streams draining the basin. The gaging station at the dam was reactivated in 1960 and has been used for flow measurements since that time.

All liquid waste handling systems, points of effluent release, and surface waters within ORNL are extensively monitored and sampled. Continuous proportional samples are collected of all process waste released to White Oak Creek and of all effluents released from White Oak Dam to the Clinch River. These samples are analyzed every 24 hours for at least gross beta activity and daily or weekly for gross alpha activity. The equipment employed in the routine analysis is capable of detecting beta particles with energies at least as low as 0.1 Mev. Continuous monitors are in operation on the Process Waste System and in White Oak Creek and White Oak Dam that are capable of detecting the beta particles (0.22 Mev) emitted by ^{147}Pm. This system of monitoring and sampling can be expected to alert Laboratory personnel to any unusual releases of radionuclides not determined in monthly composite sampling; that is, beta emitters that are shorter lived and less energetic than those normally encountered.

Until 1948, daily radiation measurements were made at White Oak Dam. Samples were collected periodically and analyzed for gross-beta activity. The number of beta curies released was calculated using mean annual discharges (daily flow measurements) and either measured or estimated gross activity content as follows: 1944, 600 curies; 1945, 500 curies; 1946, 900 curies; 1947, 200 curies; and 1948, 496 curies. Only infrequent

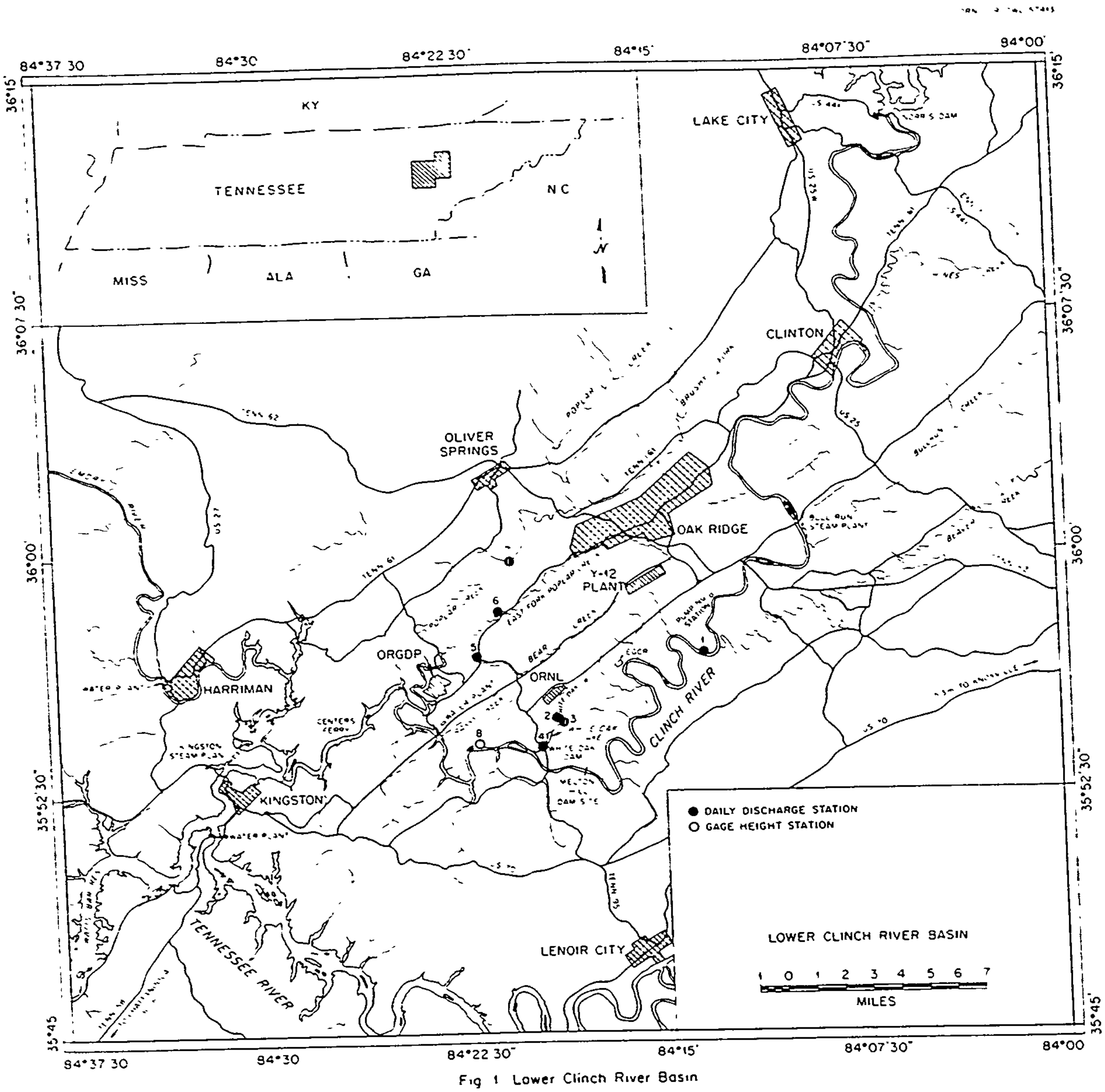


Fig 1 Lower Clinch River Basin

Fig. 1. Lower Clinch River Basin

radiochemical analyses were made. An estimate was made of the ^{90}Sr content from the average amount, 27% found to be present during the period 1949 to 1958. For the purpose of further calculations, ^{90}Sr released from 1944 to 1948 was estimated as follows: 1944, 150 curies; 1945, 120 curies; 1946, 240 curies; 1947, 60 curies; and 1948, 130 curies.

Beginning in 1949 monthly composite samples were also analyzed radiochemically for cesium, ruthenium, strontium, cobalt, trivalent rare earths (TRE), cerium, zirconium, niobium, and iodine; and the curies released each year were calculated (Table 1). The increased quantity of ^{137}Cs released in ~~1955~~ 56 was due to the draining of White Oak Lake. Subsequent reduction in release of this nuclide was associated with treatment of process waste water and partial reimpoundment of the lake. The increase in ^{106}Ru released was associated with operation of the waste pits, while the decrease in ^{90}Sr released was related to the operation of the Process Waste Water Treatment Plant and modified waste management practice. It is noteworthy that the quantity of ^{90}Sr released to the Clinch River in 1962 and 1963 was about the same as that contributed by fallout from weapons tests.

Concentrations and Potential Human Exposures Downstream

Estimates of the mean annual concentrations of radionuclides in the Clinch and Tennessee Rivers were based on dilution ratios and the fact that White Oak Creek effluent is completely mixed with river water after 3 to 5 miles of flow downstream from the mouth of the creek. This was shown by tracer tests in the Clinch River in 1958, 1961, and 1962.[9,10,11] The concentration values derived in this way are conservative, since no allowance was made for decreases of the radionuclides in the water by radioactive decay or removal with suspended sediments.

Four downstream locations were considered for the evaluation analyses (Fig. 1,2), namely: (1) Clinch River Mile (CRM) 14.5, which is 6.3 miles downstream from the White Oak Creek discharge at CRM 20.8; (2) CRM 2.6, downstream from the mouth of Emory River near Kingston Steam Plant; (3) Tennessee River Mile (TRM) 529.9, Watts Bar Dam and Resort water supply; and (4) TRM 465, at Chattanooga water supply intake and 6.0 miles downstream from Chickamauga Dam.

TABLE I

YEARLY DISCHARGES OF RADIONUCLIDES TO CLINCH RIVER (CURIES)[a]

Year	Gross Beta	^{137}Cs	^{106}Ru	^{90}Sr	TRE(-Ce)	^{144}Ce	^{95}Zr	^{95}Nb	^{131}I	^{60}Co
1949	718	77	110	150	77	18	180	22	77	
1950	191	19	23	38	30		15	42	19	
1951	101	20	18	29	11		4.5	2.2	18	
1952	214	9.9	15	72	26	23	19	18	20	
1953	304	6.4	26	130	110	6.7	7.6	3.6	2.1	
1954	384	22	11	140	160	24	14	9.2	3.5	
1955	437	63	31	93	150	85	5.2	5.7	7.0	6.6
1956	582	170	29	100	140	59	12	15	3.5	46
1957	397	89	60	83	110	13	23	7.1	1.2	4.8
1958	544	55	42	150	240	30	6.0	6.0	8.2	8.7
1959	937	76	520	60	94	48	27	30	0.5	77
1960	2190	31	1900	28	48	27	38	45	5.3	72
1961	2230	15	2000	22	24	4.2	20	70	3.7	31
1962	1440	5.6	1400	9.4	11	1.2	2.2	7.7	0.36	14
1963	470	3.5	430	7.8	9.4	1.5	0.34	0.71	0.44	14

[a]Values calculated from data supplied by Applied Health Physics Section, ORNL.

Information regarding community water systems on or near the Clinch and Tennessee Rivers downstream from ORNL to South Pittsburgh, Tennessee, is given in Table 2. At CRM 14.5 and on the Emory River in the vicinity of CRM 4.4, water supplies taken from the river are used for sanitary and industrial purposes by the Oak Ridge Gaseous Diffusion Plant and Kingston Steam Plant, respectively. There are downstream recreational areas at the Kingston waterfront, at Watts Bar Dam, and at numerous places along Watts Bar Reservoir. Also, there are large recreational areas along Chickamauga reservoir, notably just above Chickamauga Dam (CRM 471.0). The first large population center (Chattanooga, Tennessee) is located a few miles downstream from Chickamauga Dam (TRM 471.0) and is served by a public water supply taken from the Tennessee River at TRM 465. In addition, CRM 14.5, TRM 529.9, and TRM 471.0 are stations in the basic water-sampling network of the Clinch River Study. The quantity of water passing each location annually was calculated from average flow values (Table 3). The average concentration of radionuclides at each location was determined from the curies released and the total flow for each year.

In this report the calculated concentration values for two of the locations are given, namely: CRM 14.5 and TRM 465 (Tables 4 and 5). Analyses for ^{91}Y were not performed. For the purpose of estimating dose, the concentrations of ^{91}Y were assumed to be equal to the difference in the concentration of trivalent rare earths and the concentration of ^{90}Sr (in equilibrium with ^{90}Y).

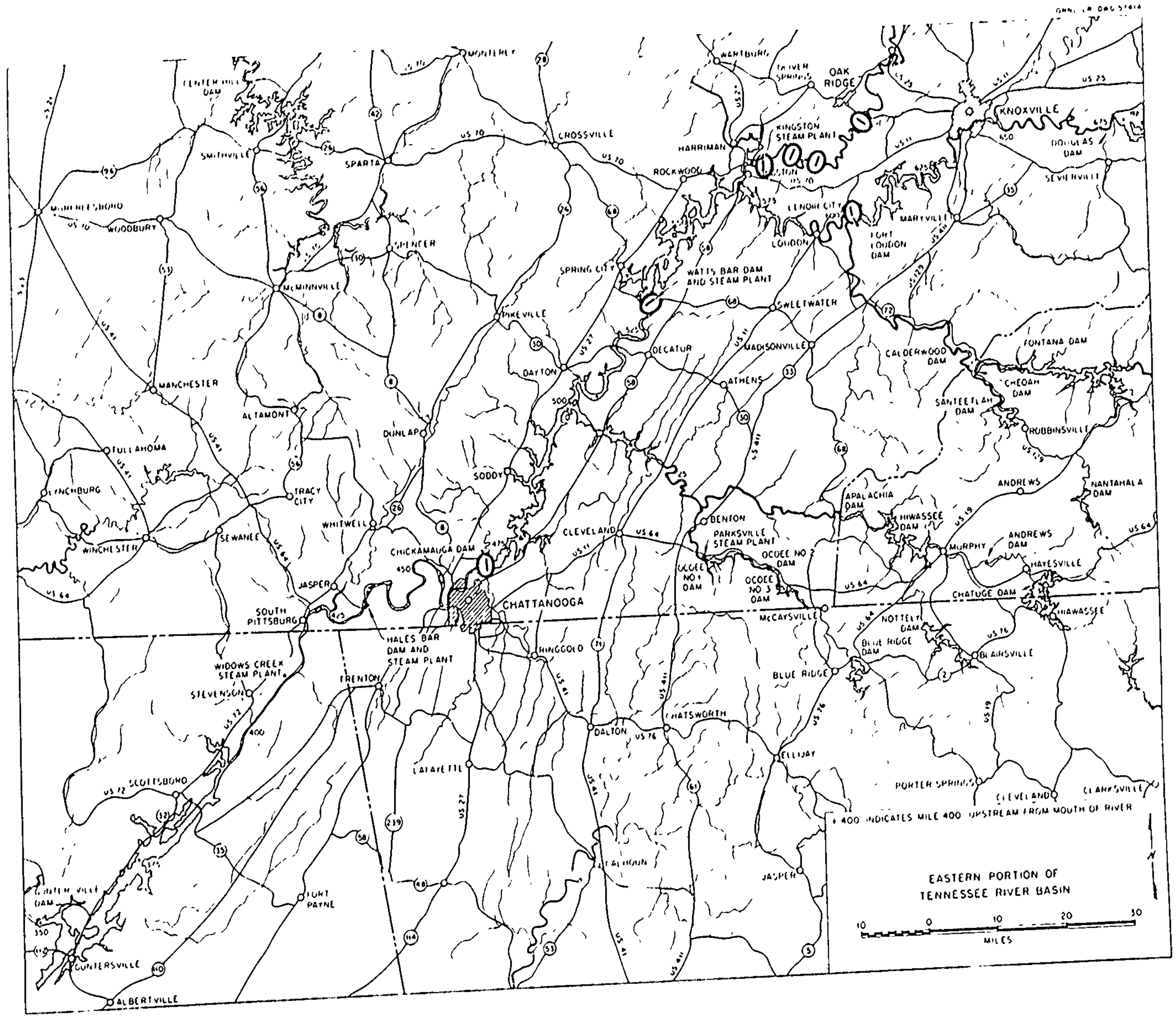


Fig. 2. Network Water Sampling Stations.

TABLE 2

COMMUNITY WATER SYSTEMS IN TENNESSEE DOWNSTREAM FROM ORNL SUPPLIED BY INTAKES ON CLINCH AND TENNESSEE RIVERS OR TRIBUTARIES THAT MAY BE AFFECTED BY MAIN STREAM CONDITIONS

Community	Intake Source		Number of Services	Population Served	Quantity (MGD)	Remarks
	Stream	Location				
ORGDP K-25	Clinch R.	CRM 14.5		3,015	4	Industrial plant potable water system.
Harriman	Emory R.	ERM 12	2,858	12,000	1.15	May at times draw Clinch R. water.
Kingston Steam Plant	Emory R.	CRM 4.4		600	.05	Potable water system.
Kingston	Tenn. R.	TRM 568.1	1,265	6,500	.29	River supplements spring supply.
Rockwood	Tenn. R.	TRM 553	2,000	7,000	1.0	River supplements spring supply.
Spring City	Piney R.	PRM 6.4	611	1,850	.15	Piney R. supplements spring supply.
Watts Bar Dam and Resort	Tenn. R.	TRM 530	25	150	.03 .14	Summer population highly variable.
Soddy-Daisy-Falling Water Walden's Ridge	Soddy Creek Embayment	TRM 488	2,545	8,000	.4	Supply approximately 3/4 from river, 1/4 from well.
Harrison Bay State Park	Tenn. R.	TRM 478		50	.05	Population highly variable. Swimming pool separate.
Booker T. Washington State Park	Tenn. R.	TRM 474			.05	Supplies swimming pool only.
Volunteer Ordnance Works-Farmers Chemical Association	Tenn. R.	TRM 473		300	37	Water used in processing.
Chattanooga	Tenn. R.	TRM 465	50,000	225,000	38.0	Includes Signal Mtn.
South Pittsburg	Tenn. R.	TRM 435	1,300	4,000	.4	

TABLE 3

MEAN ANNUAL FLOW IN CLINCH AND TENNESSEE RIVERS
(CUBIC FEET PER SECOND)

YEAR	CRM 14.5[a]	CRM 2.6[a]	TRM 529.9[b]	TRM 471.0[b]
1944	4800	6870	25690	32290
1945	4940	7020	26490	32270
1946	5150	6880	29100	38540
1947	4420	5720	24040	31190
1948	4290	6480	26370	34360
1949	5460	7560	33300	43630
1950	6630	9360	34240	44030
1951	6170	8760	28070	36560
1952	4570	5770	22470	29770
1953	4340	5710	22160	28130
1954	2990	4730	20480	26050
1955	4850	6610	23790	30530
1956	5040	7340	24750	30990
1957	6350	9300	36310	45250
1958	5560	6880	27780	34330
1959	3490	5260	23760	29000
1960	4460	6200	25150	31010
1961	4780	7110	29520	37430
1962	4980	8400	33700	40600
1963	5110	7180	25400	31600

[a]Values furnished by the United States Geological Survey - Estimated on basis of discharge records for the gaging station on Clinch River near Scarboro and intervening inflow.

[b]Values furnished by the Tennessee Valley Authority.

TABLE 4

CALCULATED MEAN ANNUAL CONCENTRATION OF RADIONUCLIDES

AT CLINCH RIVER MI. 14.5

(UNITS OF 10^{-9} μc/ml or pc/liter)

Year	Gross Beta	^{137}Cs	^{106}Ru	^{90}Sr	^{91}Y	^{144}Ce	^{95}Zr	^{95}NB	^{131}I	^{60}Co
1944	100		Bq/l	40 Bq/l						
1945	100			30						
1946	200			50						
1947	60			20						
1948	130			40						
1949	150	16	22	30	0	3.7	36	4.6	16	
1950	32	3.2	3.9	6.5	0		2.5	7.2	3.2	
1951	18	3.6	3.2	5.2	0		0.82	0.40	3.2	
1952	53	2.4	3.6	18	0	5.6	4.7	4.4	4.8	
1953	78	1.7	6.8	35	0	1.7	2.0	0.93	0.54	
1954	140	8.2	4.2	51	11	8.9	5.2	3.5	1.3	
1955	100	15	7.1	22	13	20	1.2	1.2	1.6	1.5
1956	130	38	6.5	23	7.6	13	2.6	3.4	0.78	10
1957	70	16	11	15	5.5	2.2	4.0	1.3	0.21	0.85
1958	110	11	8.4	30	18	6.0	1.2	1.2	1.7	1.8
1959	300	25	170	19	11	16	8.7	9.5	0.16	24
1960	550	7.7	480	6.9	5.1	6.7	9.3	11	1.3	18
1961	520	3.5 0.13	480 17.76	5.2 0.19	0.35	0.98	4.6	17	0.87	7.3 0.27
1962	270	1.0 0.04	260 9.62	1.8 0.07	0.30	0.23	0.40	1.4	0.067	2.6 0.10
1963	100	0.76 0.03	94 3.48	1.7 0.06	0.35	0.33	0.074	0.16	0.096	3.1 0.11

TABLE 5

CALCULATED MEAN ANNUAL CONCENTRATION OF RADIONUCLIDES

AT TENNESSEE RIVER MI. 465

(UNITS OF 10^{-9} $\mu c/ml$ or pc/liter)

Year	Gross Beta	^{137}Cs	^{106}Ru	^{90}Sr	^{91}Y	^{144}Ce	^{95}Zr	^{95}Nb	^{131}I	^{60}Co
		Bq/l		Bq/l						
1944	20			5						
1945	20			4						
1946	20			6						
1947	8			2						
1948	16			4						
1949	18	2.0	2.7	3.7	0	0.46	4.5	0.57	2.0	
1950	4.9	0.49	0.60	0.98	0		0.38	0.11	0.49	
1951	3.1	0.61	0.54	0.87	0		0.14	0.068	0.54	
1952	8.1	0.37	0.56	2.7	0	0.86	0.72	0.68	0.74	
1953	12	0.26	1.1	5.4	0	0.27	0.30	0.14	0.083	
1954	17	0.94	0.48	5.8	1.2	1.0	0.59	0.40	0.15	
1955	16	2.3	1.1	3.4	2.0	3.1	0.19	0.21	0.26	0.24
1956	21	6.2	1.1	3.8	1.2	2.1	0.42	0.55	0.13	1.7
1957	9.8	2.2	1.5	2.1	0.78	0.31	0.56	0.18	0.030	0.12
1958	18	1.8	1.4	4.8	3.0	0.97	0.20	0.20	0.32	0.28
1959	36	2.9	20	2.3	1.3	1.9	1.1	1.1	0.02	2.8
1960	79	1.1	67	1.0	0.73	0.96	1.3	1.6	0.19	2.6
1961	67	0.47 .0174	61 2.26	0.67 0.025	0.05	0.13	0.59	2.1	0.11	0.93 0.03
1962	40	0.15 .0056	38 1.41	0.26 0.01	0.044	0.034	0.059	0.21	0.010	0.38 0.01
1963	17	0.12 .00044	15 0.56	0.28 0.104	0.056	0.053	0.012	0.025	0.016	0.49 0.02

.031

AVENUES OF HUMAN EXPOSURE

Mechanisms of Exposure

The potential avenues of human exposure resulting from release of radioactivity to the environment are many and complex. H. M. Parker has indicated a number of exposure pathways and has suggested those which he believed to be of major consequence.[12] From radioactive wastes in rivers, streams, lakes, or reservoirs, he emphasizes the hazards related to use as drinking water, immersion in the water, close approach to the water (including contaminated mud and vegatation), use of water for irrigation, uptake by biological chains, industrial processes, sewage disposal, and atmospheric discharges.

The list is well conceived but, unfortunately, includes many avenues for which data are not available. An estimate of total human radiation exposure through surface waters is not possible now, and probably will not be for many years to come. However, based on available experience, the avenues of human exposure considered in the present report are believed to include the significant or potentially significant mechanisms of exposure resulting from radionuclide discharge to the Clinch River.

Critical Organs Considered

For a detailed estimate of exposure to radioactive material in the environment, it is necessary to calculate the dose to those organs for which the dose may reasonably be expected to be a maximum or to be in excess of the prescribed limits. To reduce the number of calculations, an insight concerning the potentially critical organs may be obtained by considering the type and concentration of radionuclides released, the maximum permissible concentration in water (MPC_w) for these radionuclides, the potentially significant avenues of exposures, and the type of individual under consideration. Based upon these considerations, the organs selected for analyses in this report include bone, gastrointestinal tract, thyroid, gonads, and total body. The bone and total body are reasonable selections when ^{90}Sr and ^{137}Cs are considered and when dose by immersion in contaminated fluids is possible. The increased quantity of

^{106}Ru, entering the surface water in 1960 and 1961, suggested analyses of the immersion dose and the GI tract. The genetic dose is of particular concern for exposure of a population and is included, although it can be estimated only approximately as equal to the total body dose; that is, equal to the average dose in other soft tissues. Finally, the release of ^{131}I implicates the thyroid, especially when the child is considered.

Estimation of Dosage to Organ

The fraction of MPC_w attained for the case of internal dose was calculated according to the recommendation of the ICRP.[1] For a mixture of invariant composition and based on a particular organ, x, the fraction of MPC_w that is attained is given by:

$$\sum_i \frac{P_{wi}}{(MPC)^x_{wi}} \tag{1}$$

where

P_{wi} = the concentration of the particular radionuclide in water and

$(MPC)^x_{wi}$ = the maximum permissible concentration of the particular radionuclide in water for the organ and individual of interest and for continuous exposure.

When the value of expression (1) is less than or equal to 1, the exposure is not in excess of permitted limits. This formulation neglects the dose due to external sources, which will be estimated separately in this report.

The values of P_{wi} are to be average values, the period of averaging being one year according to the recommendations of ICRP, NCRP, and FRC (Table 6 lists the maximum permissible limits recommended by ICRP and FRC) [1,2,4] Thus transient changes in these environmental levels may not be of great significance. A high concentration in the river water on a given day is an important factor for operation of the facilities, and operating personnel will want to determine whether it is due to a change in the facilities or procedures, whether it results from reduced flow in the river (loss of dilution factor), et cetera.

TABLE 6

MAXIMUM PERMISSIBLE EXPOSURE

Agency	Type of Situation	Average Dose (rem/yr)			
		Bone[a]	G. I. Tract	Total Body	Thyroid
ICRP[c]	A. Occupational Worker	30	15	5	30
	B. Plant Vicinity				
	Work in vicinity[b]	3	1.5	1.5	3
	C. Population at Large				
	Individual	3	1.5	0.5	3
	Average	1	0.5	0.17[a]	1
FRC[c]	A. Occupational Worker	30	15	5	30
	B. Population at Large				
	1. Individual				
	a. Adult	1.5		0.5	3.0
	b. Child	1.5		0.5	1.5
	2. Population average				
	a. Adult	0.5		0.17	1.0
	b. Child	0.5		0.17	0.5

[a]Multiply by 0.3 to obtain portion of dose suggested for internal sources.
[b]Or visit area occasionally.
[c]See reference list No. 1,2,3.

However, if such a single measurement is used in formula (1), the result does not represent meaningfully the actual exposure. At best it represents only the hypothetical situation that would exist if the level persisted for at least a year. The fact that only values of the concentrations P_{wi}, averaged over a period of one year, are to be used in (1), is frequently overlooked. This has led, in some cases where transient levels have been high, to gross misinterpretations and unwarranted concern by the public.

Formula (1) is easily rearranged to represent a dose rate to organ x, but, again, the formula requires careful interpretation. If the exposure situation remains unchanged for 50 years, the weekly dose received by a particular organ due to internal and external sources is given by:

$$D_{50} = \sum_i \frac{P_{wi}}{(MPC)^x_{wi}} L + \sum_j R^x_j \qquad (2)$$

where

L = the average weekly dose (rem)* permitted to the organ, and

R_j = the weekly dose (rem) received by organ x from external sources of a particular radiation type

It is clear that the formula for D_{50} as given above only applies to a long-term and stable situation. The length of the period for application depends upon the effective half-life of the radionuclide involved. In the case of the Clinch River the presence of ^{90}Sr and other bone seekers as an important contributor to the dose means that the formula for D_{50} is directly applicable only for an exposure situation which is relatively stable over a long period of years. Thus the concentrations P_{wi} should be averages representative of the concentration in river water over long periods of years, and these concentrations are supposed to be constant

*The rem is defined by the International Commission on Radiological Units (ICRU) as the unit of dose equivalent. The dose equivalent is numerically equal to the dose in rads multiplied by the appropriate modifying factors.[13]

during that period. This greatly limits the direct usefulness of the formula D_{50}.

Dose Commitment for the Future

There is, however, a second interpretation of the formula giving D_{50} which is more useful in this situation. D_{50} can be interpreted as the dose that will be received during the next 50 years due to an exposure of one week with P_{wi} and R_j^x determined only for that week. With this interpretation D_{50} is a dose commitment for the future, at least in part, rather than a dose actually received during the week the individual was present in the area. Of course, the doses from external sources, that is, the dose represented by the term, $\sum_j R_j^x$, will be received during the period of occupancy of one week and not in any subsequent period.

The first terms of D_{50} represent the doses that will result from radionuclides entering the body during the period of occupancy of one week. The dose will be delivered during various periods following the intake, depending upon the effective half life of the radionuclide involved. For example, if the radionuclide in question is ^{131}I, the dose due to this intake would be received essentially during the following three or four weeks; but if the isotope in question is ^{90}Sr, then the dose would be distributed throughout the remaining 50 years of the person's life if he lives that long. In any case D_{50} gives the total dose commitment due to the individual's occupancy of the area during this week; that is, the dose which will be received during the next 50 years following the intake resulting from this occupancy.

Corrections for Dose Estimates Based on "Standard Man"

Even with this interpretation the formula D_{50} is subject to numerous reservations and requires further interpretation. Because the MPC's which enter into the formula have been estimated only on the basis of so-called "standard man," the dose represents only that which would be received by a person of physical characteristics and habits resembling standard man. Some examples of corrections that may be necessary for standard-man estimates are mentioned below.

Such estimates of dose rates or dose commitments should be considered as average values for typical adult individuals and considerable spread about these averages is to be expected. Both the FRC and the ICRP allow a factor of 3 as a practical range to provide for the variation of dose received in a homogeneous population group. This means that among adults, children of like age, and others with comparable characteristics it is assumed that only a small fraction will receive more than 3 times the average dose. The limited data available on actual exposures suggest that the dose received by only about 5% of an adult population would exceed this factor of 3 times the average.

The formula for D_{50} does not provide for any differences due to age, sex, or other variables that may affect the intake or metabolism of the radionuclide. Perhaps the most substantial correction is that required to take account of the child, the infant, or the fetus. During these early periods of life, the organs of the body are substantially smaller than those of standard man, and in some cases the intake and metabolism do not seem to differ to the same degree from those of standard man. Thus, a fairly large correction factor may be involved. Very little is known at the present time concerning differences in metabolic rates or processes of children and adults as they relate to important radionuclides. In this report it is not possible to make any adjustment on this basis. In the few cases where bits of data are available on children and infants, the difference of their metabolic rates from those of adults does not appear to be large. There remains, however, the difference due to intake and organ size. The charts shown in Fig. 3,4, and 5 have been prepared by M. J. Cook (of ORNL) to illustrate the magnitude of these differences as estimated on the basis of data at hand. The chart indicates a base line which represents the ratio of intake to organ weight for standard man. The curve represents the correction factor which adjusts for the change of this ratio with age. Assuming, as above, that metabolism is not substantially different for the infant or child, this graph gives a correction factor which can be applied to the dose estimate

$$\sum_i P_{wi} L/(MPC)_{wi}^{x}$$

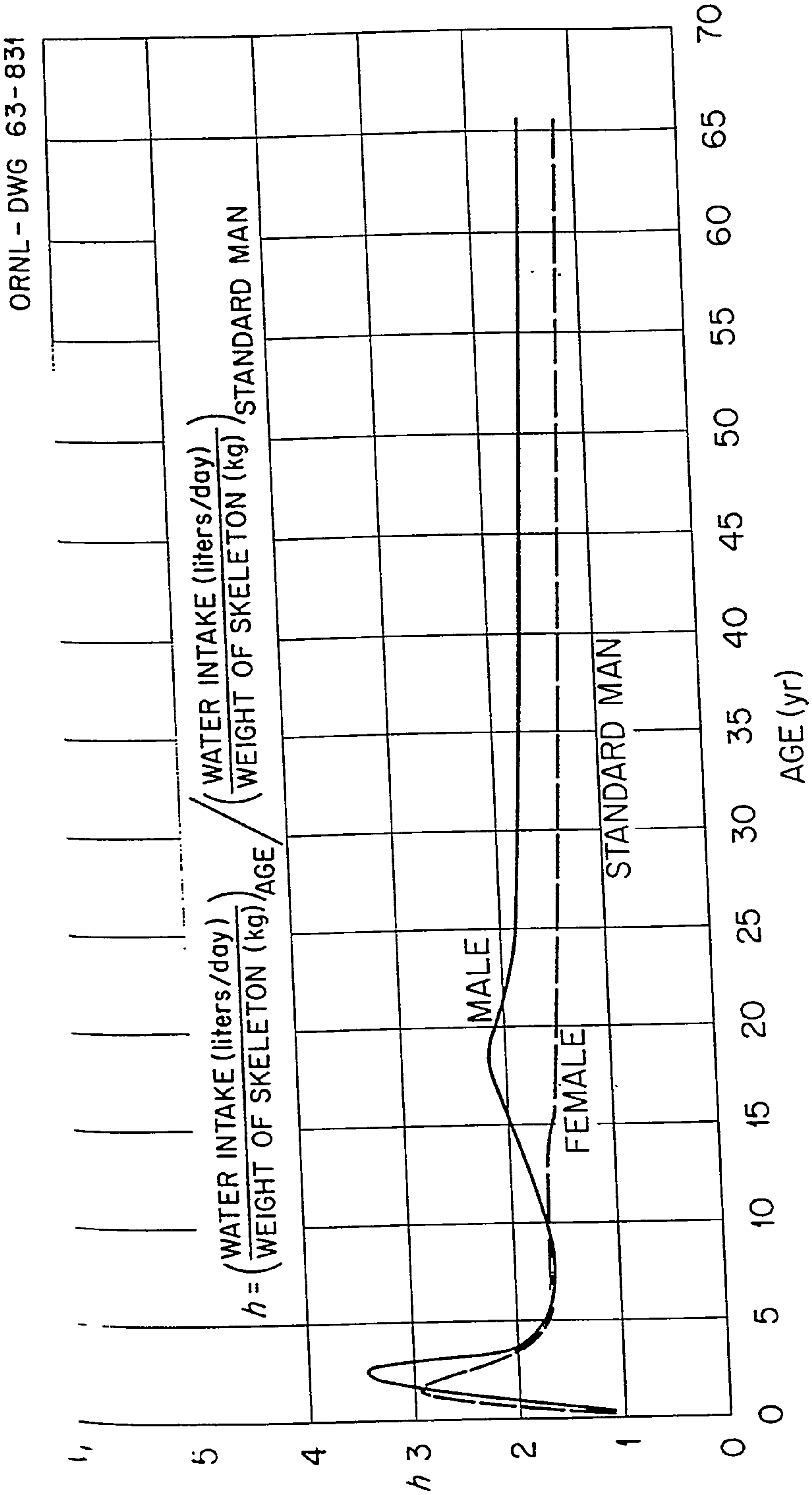


Fig. 3. Dose Correction Factor for Skeleton

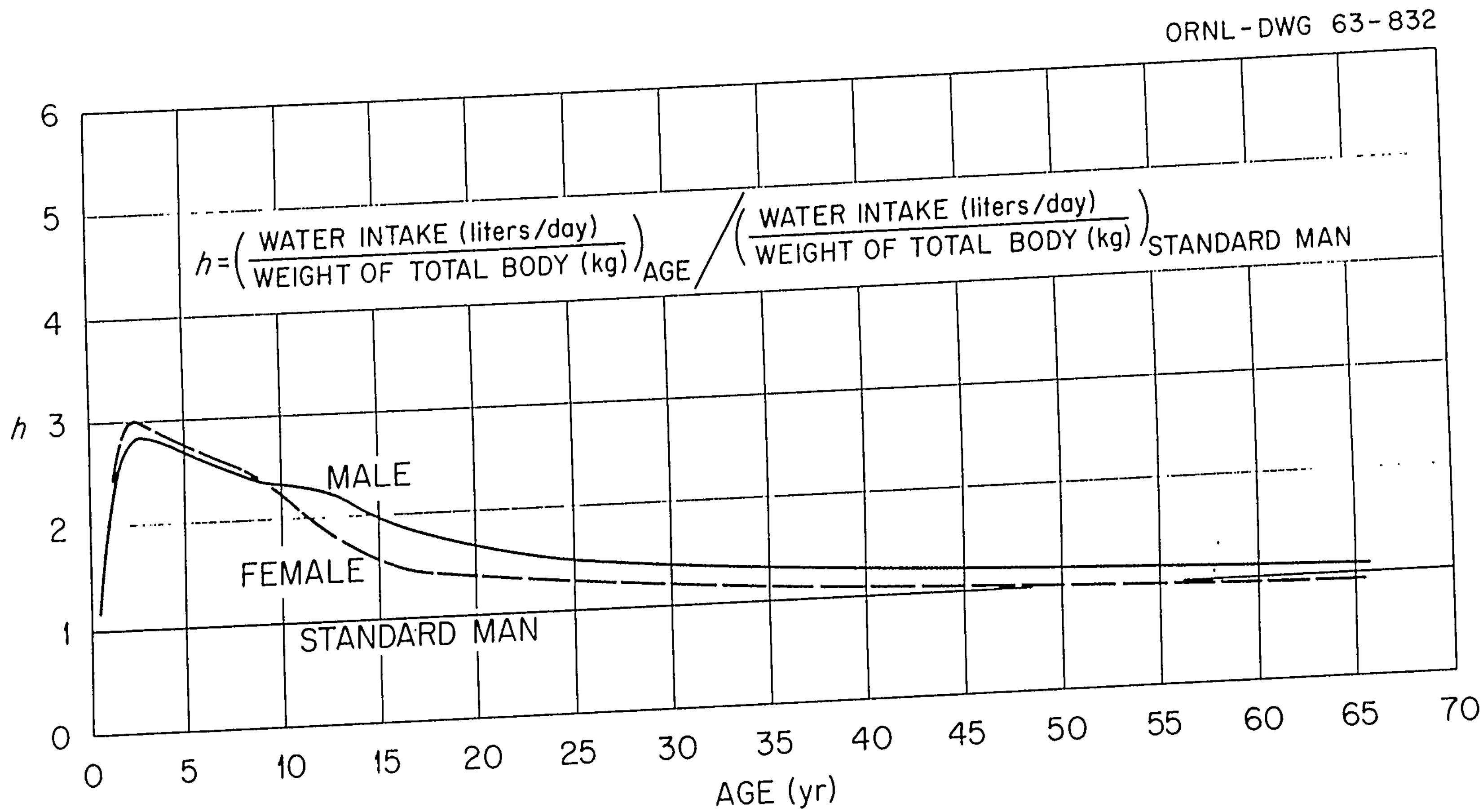


Fig. 4. Dose Correction Factor for Total Body.

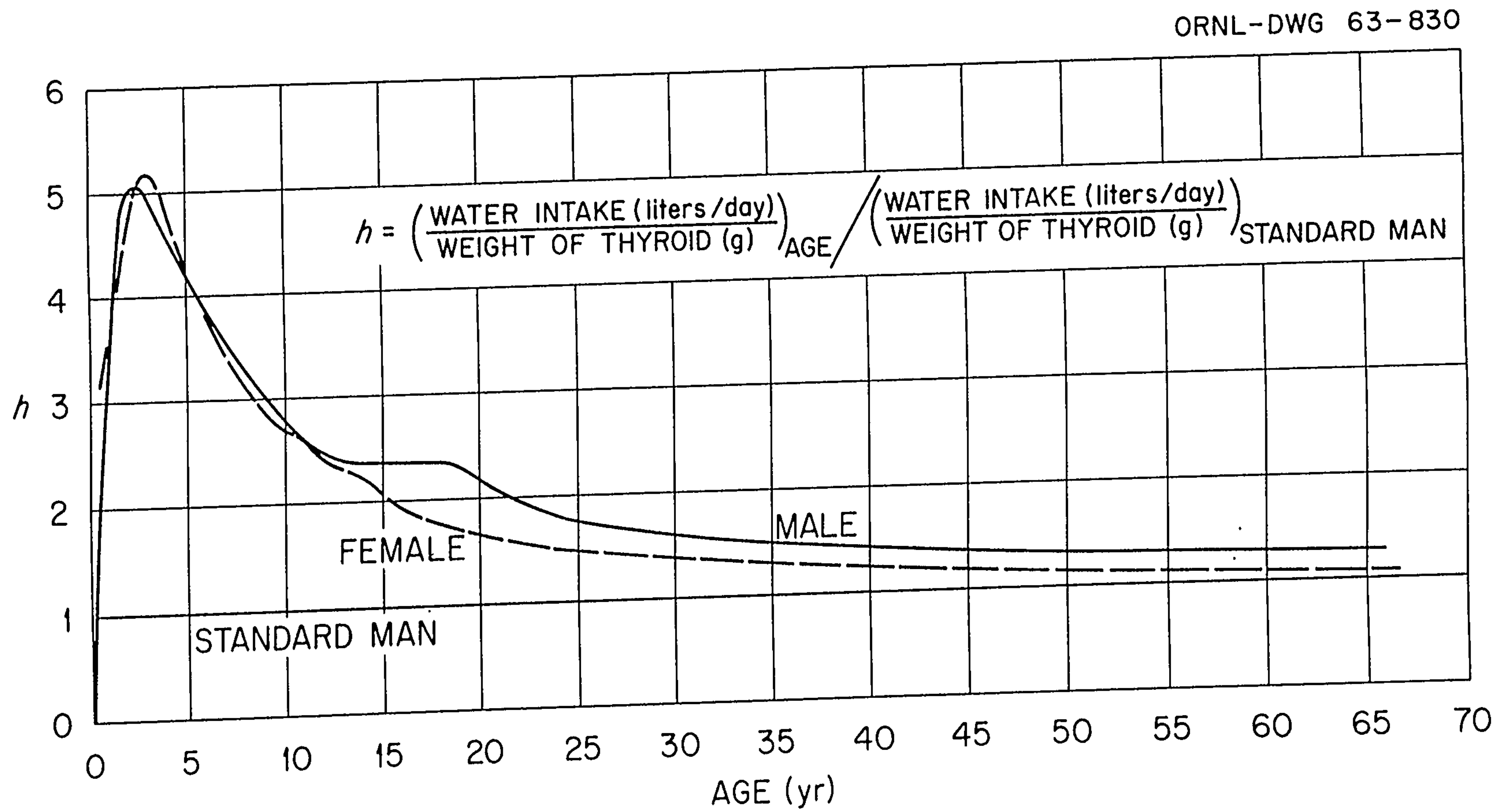


Fig. 5. Dose Correction Factor For Thyroid.

in the formula for D_{50} making it applicable for individuals of various ages. No very significant correction factor need be applied to the terms $\sum_j R_j^x$ so far as body size is concerned.

It is apparent from Figs. 3,4, and 5 that there is a significant correction to be made for infants and young children when dose to the skeleton, thyroid, or total body (genetic dose) is in question. The data on organ weights were taken from references supplied by M. J. Cook[14,15,16] and the data on water intake were obtained by the USPHS.[17]

In the case of the gastrointestinal tract, the calculation of the MPC is based on the assumption that the wall of the tract will receive 50% of the beta-gamma dose and 0.5% of the alpha particle dose delivered to the contents of the tract. To a very large extent this dose will be proportional to the concentration of the radionuclide in the contents of the tract. It will not vary greatly with the mass of the contents or with the diameter of the tract. Thus no very significant correction is necessary so far as the masses of the organ or contents are concerned. Assuming the tract is always full and that the residence time is short compared to the half-life of the radionuclides of interest, the dose received will not be changed significantly as residence time varies. This leaves the concentration of the radionuclide in the contents of the tract, and, hence, the dietary composition as the only variable of significance.

The ratio

$$\left(\frac{\text{Intake of Water}}{\text{Weight of Contents of GI Tract}}\right)_{\text{age}} \Bigg/ \left(\frac{\text{Intake of Water}}{\text{Weight of Contents of GI Tract}}\right)_{\substack{\text{standard}\\ \text{man}}}$$

would seem to be the appropriate correction factor to apply here. No data have been found on the variation of the weight of the contents of the GI tract with age.

Maximum Permissible Limits for Internal Exposures

Table 7 gives the fraction of $(MPC)_w$ of the river water calculated by using the average concentration of the various radionuclides for each year where such data were available. All $(MPC)_w$ values used for data relating

TABLE 7

FRACTION OF MPC IN WATER FROM CLINCH AND TENNESSEE RIVERS

Year	Clinch River Mi 14.5				Tennessee River Mi 465.5			
	Bone	G. I. Tract	Total Body	Thyroid	Bone	G. I. Tract	Total Body	Thyroid
1944	0.1		0.06	0.02	0.04		0.07	0.006
1945	0.08		0.04	0.01	0.03		0.06	0.005
1946	0.1		0.07	0.02	0.05		0.09	0.008
1947	0.05		0.03	0.01	0.02		0.03	0.003
1948	0.1		0.06	0.02	0.03		0.06	0.005
1949	0.076	0.0043	0.044	0.021	0.028	0.0016	0.054	0.0077
1950	0.016	0.0022	0.0094	0.0043	0.0073	0.0010	0.014	0.0021
1951	0.013	0.0017	0.0075	0.0038	0.0066	0.00087	0.013	0.0019
1952	0.044	0.0015	0.025	0.0098	0.020	0.00069	0.039	0.0045
1953	0.087	0.0018	0.050	0.015	0.040	0.00053	0.076	0.0053
1954	0.13	0.0032	0.072	0.022	0.044	0.0011	0.083	0.0074
1955	0.054	0.0037	0.032	0.0099	0.026	0.0019	0.050	0.0047
1956	0.059	0.0042	0.035	0.010	0.029	0.0020	0.057	0.0051
1957	0.037	0.0024	0.022	0.0063	0.016	0.00099	0.030	0.0027
1958	0.074	0.0031	0.043	0.013	0.034	0.0015	0.069	0.0077
1959	0.049	0.021	0.029	0.0084	0.018	0.0075	0.034	0.0030
1960	0.017	0.050	0.011	0.0037	0.0076	0.021	0.015	0.0016
1961	0.013	0.048	0.0077	0.0027	0.0050	0.019	0.0099	0.0010
1962	0.0044	0.026	0.0028	0.00083	0.0023	0.013	0.0040	0.00037
1963	0.0043	0.0096	0.0026	0.00093	0.0024	0.0052	0.0042	0.00038

TABLE 8

Maximum Permissible Concentrations of Radionuclides in Water[a]

(μc/ml)

Source of Supply	Nuclide	Critical Organ: Bone	Total Body	G. I. Tract	Thyroid
Clinch River	^{90}Sr	4×10^{-7}	7×10^{-7}	4×10^{-5}	2×10^{-6}
	^{89}Sr	1×10^{-5}	7×10^{-5}	3×10^{-5}	4×10^{-4}
	^{137}Cs	5×10^{-5}	2×10^{-5}	4×10^{-5}	1×10^{-4}
	^{106}Ru	1×10^{-3}	2×10^{-3}	1×10^{-5}	1×10^{-2}
	^{60}Co	6×10^{-4}	1×10^{-4}	3×10^{-5}	6×10^{-4}
	^{131}I	1×10^{-3}	2×10^{-4}	6×10^{-5}	2×10^{-6}
	^{95}Zr	2×10^{-1}	1×10^{-1}	6×10^{-5}	6×10^{-1}
	^{95}Nb	7×10^{-1}	4×10^{-1}	1×10^{-4}	2
	^{144}Ce	8×10^{-3}	3×10^{-2}	1×10^{-5}	2×10^{-1}
	^{91}Y	3×10^{-2}	2×10^{-1}	3×10^{-5}	1
Tennessee River	^{90}Sr	1×10^{-7}	7×10^{-8}	1×10^{-5}	8×10^{-7}
	^{89}Sr	3×10^{-6}	7×10^{-6}	1×10^{-5}	1×10^{-4}
	^{137}Cs	2×10^{-5}	2×10^{-6}	1×10^{-5}	4×10^{-5}
	^{106}Ru	3×10^{-4}	2×10^{-4}	3×10^{-6}	4×10^{-3}
	^{60}Co	2×10^{-4}	1×10^{-5}	1×10^{-5}	2×10^{-4}
	^{131}I	4×10^{-4}	2×10^{-4}	2×10^{-5}	7×10^{-7}
	^{95}Zr	7×10^{-2}	1×10^{-2}	2×10^{-5}	2×10^{-1}
	^{95}Nb	3×10^{-1}	4×10^{-2}	3×10^{-5}	8×10^{-1}
	^{144}Ce	3×10^{-3}	3×10^{-3}	3×10^{-6}	6×10^{-2}
	^{91}Y	1×10^{-2}	2×10^{-2}	1×10^{-5}	4×10^{-1}

[a]As recommended by ICRP (see Reference 1) values of MPC_w for continuous occupational exposure are reduced to 1/10 and applied to the Clinch River and are reduced to 1/30 for bone, thyroid, and G. I. tract as critical organ and to 1/100 for whole body as critical organ and applied to the Tennessee River. When the organ of reference is not listed in ICRP Publication 2 an independent estimate of the corresponding MPC_w value for continuous occupational exposure is obtained from the expression L^x (MPC)w TB/0.1, where L^x is the weekly dose rate permitted to organ x and $(MPC)_w$TB is the maximum permissible concentration in water for total body.

to the Clinch River (see Table 8) are taken as 1/10 of the occupational $(MPC)_w$ values for exposure during the entire week (168 hours). To obtain $(MPC)_w$ values relating to the Tennessee River, the $(MPC)_w$ for continuous occupational exposure (168 hours/week) has been multiplied by 1/100 for whole body as critical organ and by 1/30 with thyroid, bone, and GI tract as the critical organs. These values are suggested by ICRP for application to exposure of persons living in the neighborhood of the plant, or for the average exposure of the population at large, respectively. If the fraction of $(MPC)_w$ given in Table 7 is multiplied by the appropriate dose rate from Table 6, an annual dose rate is obtained. However, it must be borne in mind that in the case of radionuclides of long effective half-life, this annual dose rate will be attained only if occupancy continues for many years. While the FRC has not extended recommendations to many of the radionuclides of interest here, it has recommended that Federal Agencies use the recommendations of the NCRP and the ICRP in such cases. In a few cases where intake values recommended by the FRC are available and differ from recommendations of the ICRP and NCRP, a slight adjustment of the present values will be necessary to obtain dose estimates by the procedure used by FRC.

To obtain values of dose commitment for children, an additional factor must be applied as indicated by Figs. 3, 4, 5. It must be realized that these values for a child only apply during a relatively short period of life. For ^{131}I the annual dose to an individual child's thyroid might be as high as 12 times the average dose to the thyroid of an adult, but this would be only during the first year or two of life, and even during these years most infants less than 2 years of age would only be at a level of 4 times the average adult value. For bone, the situation is more complicated. The factor of 4 applies only during the years of age from, say, 10 to 20, and it is unlikely that an equilibrium situation would be reached in the bone. Thus the annual doses to bone of an individual child during these years might be expected to be less than 12 times the average adult values. However, the dose commitment for the future would be increased by the full factor of 4 for the average teen-ager and by a factor of 12 for the higher group of teen-agers. This additional dose would be received over many subsequent years of the individual's life span.

Comparison of Internal Dose Recommendations of FRC and ICRP

The FRC has recommended a set of Radiation Protection Guides (RPG) applicable to normal peacetime operations. In Report No. 1, RPG values are given for occupational exposure as well as for exposure of the gonads or the total body in the case of population exposure.[2] These values are identical with those recommended by the ICRP.[18] In Report No. 2, specific guidance is given in connection with exposure of population groups to ^{226}Ra, ^{131}I, ^{90}Sr, and ^{89}Sr.[3] RPG values are listed for single-organ exposure of the thyroid, bone, and bone marrow.

For the case of the thyroid gland and ^{131}I, the FRC recommends a RPG value of 1.5 rem per year for individuals and 0.5 rem per year for the average of suitable samples of an exposed group.[3] These values are half the corresponding guides suggested by the ICRP for exposure of the population, since the suitable samples of FRC includes only children.[19] According to FRC, "...80 picocuries of ^{131}I per day would meet the RPG for thyroid for averages of suitable samples of an exposed population group of 0.5 rem per year." For adults, the RPG for the thyroid would not be exceeded by rates of intake higher by a factor of 10; that is, 800 picocuries per day. Based upon ICRP calculations, an MPC_w value for standard man that is equivalent to 0.5 rem per year is 3.3×10^{-7} μ c per milliliter; or a daily intake of about 730 picocuries.[1] Within the precision of the data employed by these agencies in arriving at these respective guides or limits this difference in rate of intake is not significant. Notice that the dose calculated by equations 8 and 10 apply to standard man and include a term, g_t, to account for the fraction attained of permissible intake. A dose-correction factor is then applied to these equations to account for differences in the intake and organ size of the individuals under consideration. The calculated doses to the thyroids of child and man due to ^{131}I are compatible with recommendations of both agencies even though differences in the radiosensitivity of the thyroid are not considered.

For the case of the bone and ^{90}Sr, FRC recommends an RPG value of 1.5 rem per year for individuals and 0.5 rem per year for averages of exposed populations.[3] No distinction is made between dose to the bone of children and adults. They consider that a continuous dietary intake of 600 picocuries per day would generally correspond to a bone dose of 0.5 rem per year to the average of suitable samples of an exposed population. The ICRP suggests that for somatic dose the average permissible level for large populations be one-thirtieth of the continuous occupational value; that is, about one rem per year to the bone. According to Publication 2 of ICRP the rate of intake of ^{90}Sr by standard man corresponding to a dose at equilibrium of 0.5 rem per year is 40 picocuries per day.[1] However, the MPC_w value and thus the rate of ^{90}Sr intake by standard man was changed in Publication 6 of ICRP.[5] They now consider that metabolic data provides a better estimate of MPC values for ^{90}Sr (bone as critical organ), than the single exponential model used previously. Although the MPC_w value was increased by a factor of four the permissible body burden and resultant dose to the bone remain unchanged. Thus the permissible intake of ^{90}Sr by standard man was increased by a factor of four and a daily intake of 160 picocuries now corresponds to a dose of 0.5 rem per year. At present the ICRP uses a relative damage factor of 5 for bone-seeking radionuclides other than radium. The maximum permissible body burden and the associated maximum permissible intake of ^{90}Sr is weighted by a relative damage factor of 5. Thus to compare the guides offered by FRC and ICRP it is necessary to multiply the daily intake of 160 picocuries of ICRP by a factor of 5. In view of the uncertainty concerning the body burden of ^{90}Sr and the effect associated with the corresponding dose to the bone of adults at equilibrium, the discrepancy in rates of intake (600 pc per day and 800 pc per day) is not considered significant. The rate of intake and resultant bone dose suggested by the two agencies are not compatible even though there is an apparent difference of two in the standard to be applied to the exposed population.

RADIATION EXPOSURES FROM ORDINARY USAGE OF THE RIVERS

Evaluation of Dosages from Drinking Water

Estimates of the fraction of maximum permissible dosages received from drinking Clinch River and Tennessee River water are based on concentrations of radionuclides in the raw water. This approach is conservative, because it assumes that there will be no reduction of radionuclides in the water by water treatment before drinking, and it makes no allowance for portions of the radionuclides that are in the bottom sediments which would not be expected to enter raw-water intakes. Future calculations may consider radionuclide removal by water plants and bottom sediments, but the data now available do not warrant it.

The fraction of MPC_w that would be attained by drinking water from the Clinch and Tennessee Rivers at the two reference stations, namely CRM 14.5 and TRM 465, have been given in Table 7. For the period 1943-1948, only estimates of ^{90}Sr concentrations are available. Thus the fraction of MPC_w attained for this period is based on the estimates of ^{90}Sr. Such calculations are warranted only because ^{90}Sr has been responsible for almost all the bone and total body dose as well as a significant part of the dose to the thyroid. Inherent in the calculation of these fractional values is the assumption that exposure is continuous for a period of 50 years to the mixture of radionuclides that is present during the particular year. For these mixtures of radionuclides in the raw water, estimated dose to the bone constitutes a greater fraction of the maximum permissible limit than does the estimated dose to the other body organs. This is attributable to ^{90}Sr released. The largest fraction of bone dose attained was 0.13 (13%) for the 1954 concentrations, assuming that the same concentrations continued for 50 years. For example, applying the most restrictive FRC limit of thyroid dose (for the average child of the population-at-large which is 1/60 of the continuous occupational exposure), the fraction of MPC_w that would be attained at CRM 14.5 during 1961 is less than 0.03 (3%). The increase in internal dose to the GI tract for 1960 and 1961 is due to the increased release of ^{106}Ru.

Estimation of Radiation Dose from Ingestion of Water

The MPC_w values are set by the requirement that in an environment where the level of contamination remains constant and the composition of the contaminants is unchanged, the dose rate (rems/week) for an adult after 50 years of exposure shall not exceed a recommended limit. During such a 50-year exposure period, equilibrium in the body is reached by most of the radionuclides, because their effective half life in the body is short compared to 50 years. However, in the case of ^{90}Sr, the allowable annual dose rate is reached only after 50 years of continuous exposure of an adult to the MPC_w. At earlier times the dose rate to the skeleton or total body of such an adult will be below the recommended limiting dose. For this reason, and also because the levels and composition of the contaminants are not constant, estimation of dose received by ingestion of known concentrations is desirable. A mathematical model has been developed that will allow calculation of dose received as a function of time.

Following ingestion of water, the activity present in a critical organ of the body at time t(after the start of ingestion) can be expressed as:[1,20]

$$Q = f_w \ S \ X \int_0^t e^{-\lambda_e t'} \, dt', \qquad (3)$$

where

$Q = \mu c$ present in critical organ,

f_w = fraction of ingested radionuclide that is retained in the critical organ,

S = rate of intake of water, ml/yr

X = concentration of radionuclide in water during exposure, $\mu c/ml$

λ_e = effective decay constant of radionuclide, 1/yr, and

t' = a time variable.

Assuming that the concentration of a radionuclide in water is the average annual concentration and the rate of water intake is 2.2 liters/day (standard man), Eq. 3 is integrated over a time period of 1 year giving:

$$Q(I)_t = \frac{f_w \, S \, \overline{X}_t}{\lambda_e} \left[1 - e^{-\lambda_e} \right], \tag{4}$$

where

$Q(I)_t$ = μc present in the critical organ at the end of t years due to the intake of water during that year, and

$\overline{X}_t$ = average annual concentration $\mu c/ml$ of a radionuclide in water during a particular year, t.

After the exposure period t, the quantity of radionculide remaining in the critical organ is given by:

$$Q(A)_{t,\tau} = Q(I)_t e^{-\lambda_e \tau} \tag{5}$$

where

τ = the years after a particular intake period, t, and $1 \leq \tau \leq n$. Since the quantity of water consumed by an individual is a function of the individual's age, the critical-organ burden is also a function of the individual's age. Thus, an intake correction factor j_γ (where γ is the individual's age during a particular intake period), must be applied to Eqs. (4) and (5). For example, assume that an individual of age $\gamma = 10$ began to consume contaminated water at the beginning of year, t = 1, the critical-organ burden of a particular radionuclide each year for a period of, say, 3 years would be determined as follows:

Period	Body Burden (μc)	
t = 1	$j_{10}\, Q(1)_1$	
t = 2	$j_{11}\, Q(1)_2 + j_{10}\, Q(A)_{1,1}$	(6)
t = 3	$j_{12}\, Q(1)_3 + j_{10}\, Q(A) + j_{11}\, Q(A)_{2,1}$	

The dose received by the critical organ during the period of intake, t, is

$$D(I) = \frac{MPD}{qf_2} \int_o^t Qdt', \tag{7}$$

where

MPD = the maximum permissible dose rate to a particular organ, rem/yr, and

$$qf_2 = \frac{MPC_w\ S\ f_w}{\lambda_e} \left[1 - e^{-\lambda_e 50} \right],$$ the fraction of radionuclide in the critical organ after 50 years of continuous exposure.

By substituting Eq. (3) in Eq. (7) and integrating over an exposure period of 1 year, the dose received by the critical organ during a particular exposure year, t, is

$$D(I)_t = \frac{MPD\ g_t}{1 - e^{-\lambda_e 50}} \left[1 - \frac{1 - e^{-\lambda_e}}{\lambda_e} \right], \tag{8}$$

where

$g_t = \frac{\bar{X}_t}{MPC_w}$, the fraction of MPC_w in water during a particular year, t.

After the exposure period t the critical organ will continue to be irradiated by the radionuclide retained from the exposure period (see page 17). The length of time for such residual exposure depends on the effective half life of the radionuclide. The dose after exposure is

$$D(A)_{t,\tau} = \frac{MPD\ g_t\ \lambda_e}{1 - e^{-\lambda_e 50}} \int_o^t e^{-\lambda_e t'}\ dt' \int_{\tau-1}^{\tau} e^{-\lambda_e t''}\ dt'', \tag{9}$$

where

t' and t'' = time variables.

Integration of Eq. (9) over an exposure period of 1 year and post exposure period, τ, gives

$$D(A)_{t,\tau} = \frac{MPD\ g_t \left[1 - e^{-\lambda_e} \right]}{\lambda_e \left[1 - e^{-\lambda_e 50} \right]} \left[e^{-\lambda_e(\tau-1)} - e^{-\lambda_e \tau} \right] \tag{10}$$

The total dose received by a particular critical organ to a particular radionuclide after a number of years of exposure is then the sum of Eqs. (8) and (10). A dose-correction factor must be applied to Eqs. (8) and (10) to account for differences in the intake and organ size of the individuals under consideration. The dose correction factor is

$$h_\gamma = \frac{S_\gamma / M_\gamma}{S_{sm} / M_{sm}}, \tag{11}$$

where

S_γ = the rate of water intake of an individual of age, γ

S_{sm} = the rate of water intake of standard man,

M_γ = the weight of the critical organ of an individual of age, γ, and

M_{sm} = the weight of the critical organ of standard man.

For an individual of age, $\gamma = 10$, who began to consume contaminated water at the beginning of year, $t = 1$, the dose received each year for a period of, say, 3 years would be determined as follows:

Period	Dose
$t = 1$	$h_{10} D(I)_1$
$t = 2$	$h_{11} D(I)_2 + h_{10}(M_{10}/M_{11})\ D(A)_{1,1}$
$t = 3$	$h_{12} D(I)_3 + h_{10}(M_{10}/M_{12}) D(A)_{1,2} + h_{11}(M_{11}/M_{12}) D(A)_{2,1}$

(12)

Computer Calculations of Internal Dose

The mathematical models (equations 4, 5, 8 and 10), with appropriate correction factors, are coded for Data Control 1604, permitting machine computations of critical organ burdens and dose received. Calculations are performed by assuming that individuals from birth through age 45 and standard man began in 1944 to drink untreated water from the Clinch River (mile 14.5) and from the Tennessee River (mile 465). They continue to drink water from these sources through 1963, following which water is obtained from an uncontaminated supply. It is also assumed that all water taken into the body in food or drink is equally contaminated and that intake and organ mass vary with age according to data in Figures 3, 4, and 5.

Comparative Examples of Computed Dose.- Examples of the computed annual dose received by the skeleton, total body, and thyroid of males drinking Clinch River water are shown in Figures 6, 7, and 8. At the end of 1963 the dose rate to the skeleton (Fig. 6) of the critical population group, the 14-year-old, is about twice that of standard man. The dose rate received by the male skeleton of other age groups is less than the 14-year-old (see Table 9). The differences in dose rate are attributed to differences in intake and size of the skeleton. Strontium-90 is responsible for more than 99% of the skeleton dose; thus, smaller releases of this radionuclide in 1950 to 1952 and 1960 to 1963 are reflected by a reduction in annual dose received by the skeleton. Notice that the maximum dose rate to the skeleton of the potentially critical group is considerably less than 1/10 of the permissible continuous occupational levels of ICRP (3.0 rem per year). Dose rate to the total body (Fig. 7) and thyroid (Fig. 8) of the critical groups in 1963 is about 50% greater than that of standard man. Dilution of wastes in the Tennessee River results in a reduced dose rate (by a factor of about 8) to the individual organs. The differences in dose rates received by the organs are similar to those found for the Clinch River (Table 9). In all cases the dose rates to the critical organ of the potentially critical groups is at least one order of magnitude below permissible levels. The dose rate received by males is greater than that received by females of all

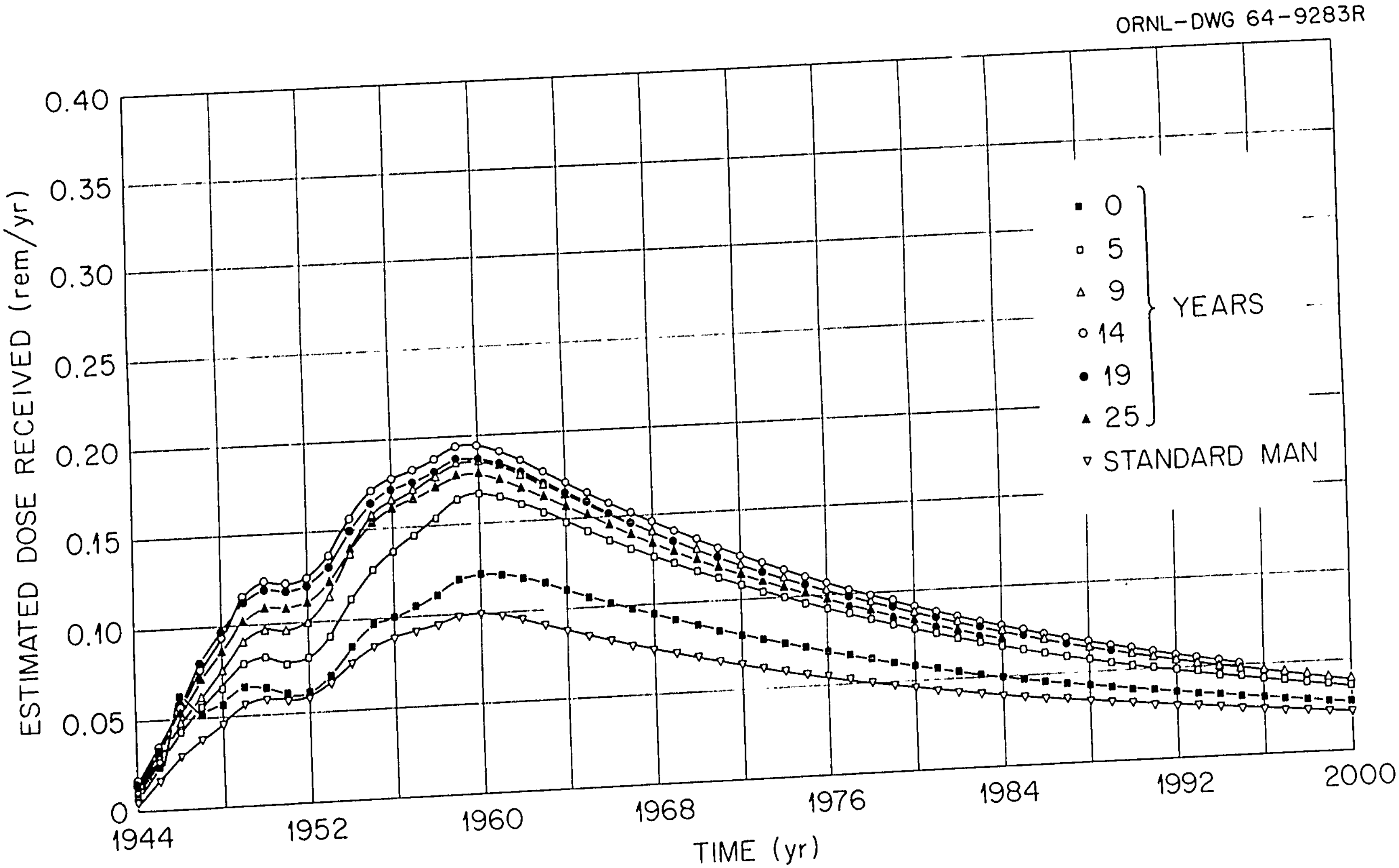


Fig. 6. Estimated Dose Received by Skeleton of Males from Drinking Clinch River Water.

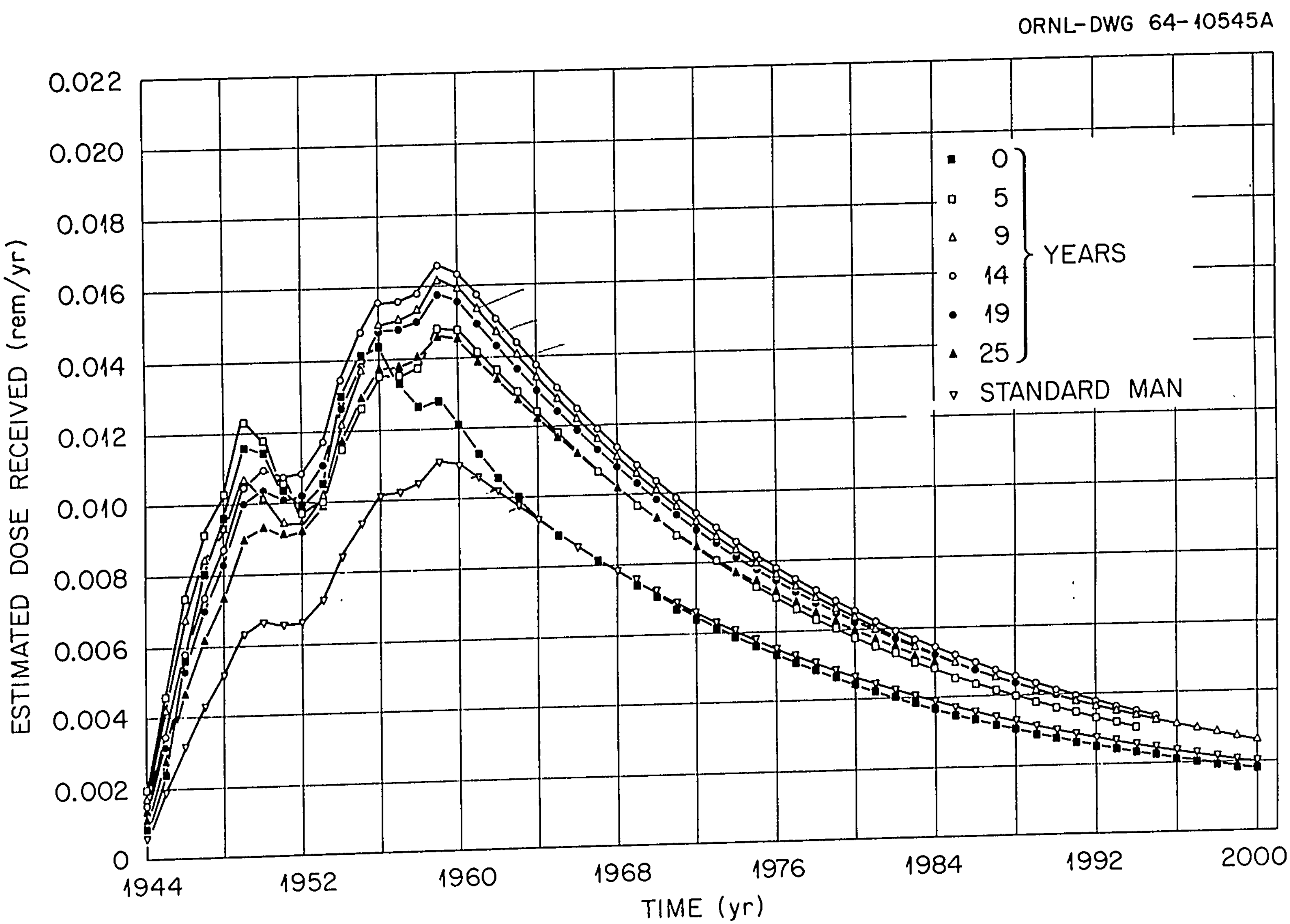


Fig. 7. Estimated Dose Received by Total Body of Males from Drinking Clinch River Water.

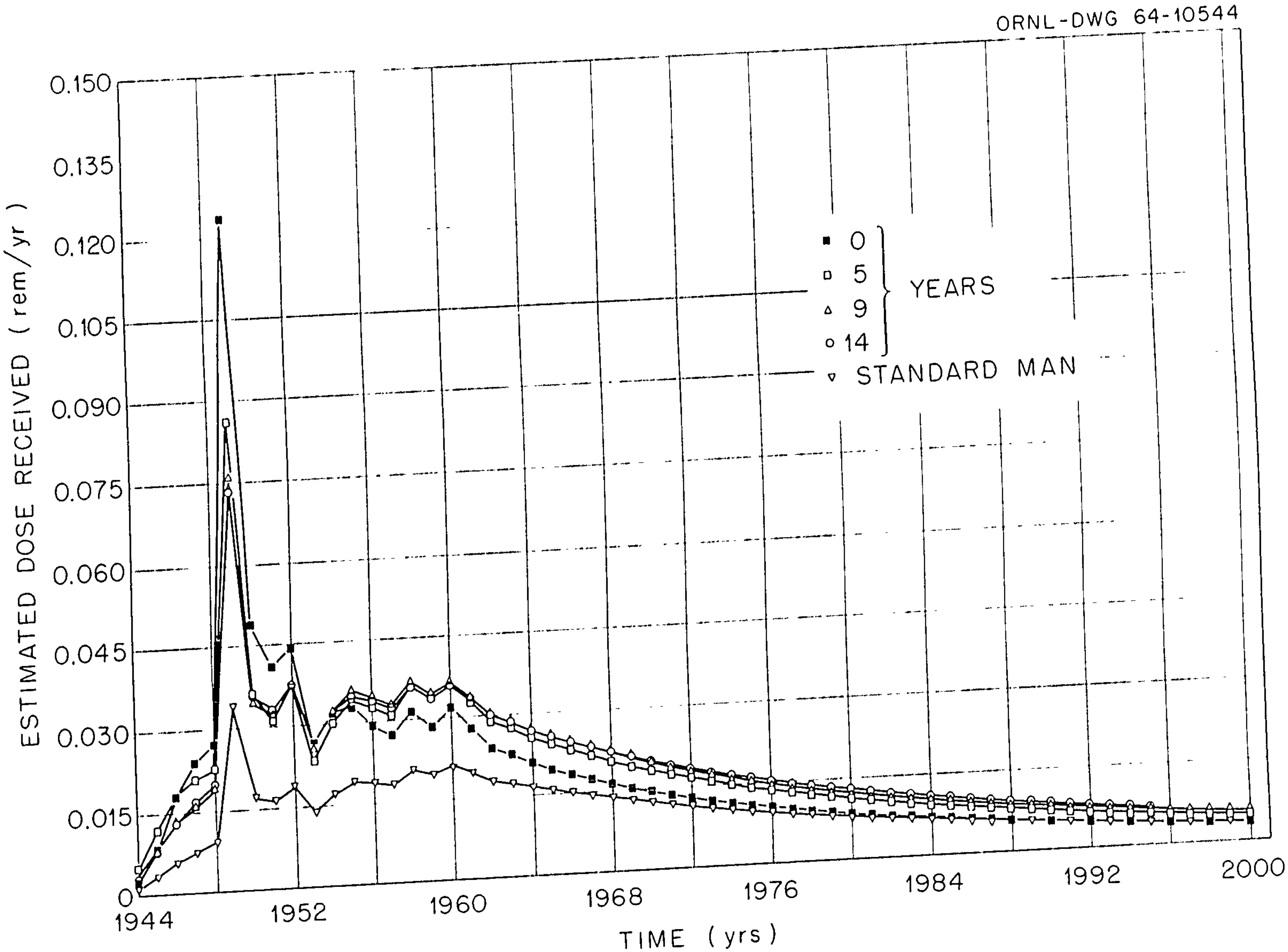


Fig. 8. Estimated Dose Received by Thyroid of Males from Drinking Clinch River Water.

TABLE 9

DOSE RATE TO CRITICAL ORGANS OF MALES FROM DRINKING WATER[a]

(rems/year)

Age at Start of Exposure	Clinch River Water			Tennessee River Water		
	Skeleton	Total Body	Thyroid	Skeleton	Total Body	Thyroid
0	0.16	0.0097	0.023	0.017	0.0014	0.0032
5	0.17	0.013	0.027	0.023	0.0018	0.0038
9	0.18	0.014	0.029	0.025	0.0019	0.0039
14	0.19	0.014	0.028	0.026	0.0019	0.0039
19	0.18	0.014	0.027	0.025	0.0018	0.0037
25	0.17	0.013	0.025	0.023	0.0017	0.0034
Standard Man	0.099	0.0097	0.017	0.013	0.0013	0.0024
Maximum Permissible Dose[b]	3.0	0.5	3.0	1.00	0.05	1.0

[a]The dose rate at the end of 1963.

[b]According to recommendations of the ICRP Publication 2 where values of annual dose rate for continuous occupational exposure are reduced to 1/10 and applied to the Clinch River and reduced to 1/30 for skeleton and thyroid as critical organ and to 1/100 for whole body as critical organ and applied to the Tennessee River.

age groups and critical organs considered.

Another interesting comparison is the total dose received by individuals during the period in which Clinch River and Tennessee River water is consumed. As shown in Table 10 the skeleton of a 14-year-old male receives a total dose of 2.9 rem by use of Clinch River water and 0.37 rem by use of Tennessee River water -- about twice that of standard man. About 99% of the total body dose is due to ^{90}Sr, and fluctuations in dose rate reflect changes in ^{90}Sr release as well as differences in intake and organ mass. The thyroid of the newborn infant receives the largest dose, about twice that of standard man. Strontium-90 and iodine-131 are responsible for 70% and 30% of the total thyroid dose, respectively. A large release of ^{131}I and the short effective half life of this radionuclide result in sizeable increase in thyroid dose during 1949. Of the organs analyzed, the skeleton of man receives the largest dose. After 1963 doses received by the critical organs is due to radionuclides that have accumulated during the period that contaminated water is consumed. This dose commitment should be considered in any assessment of future exposure likely to be received.

Consideration of Metabolic Factors

Recently information on metabolic processes of children and adults permits a preliminary assessment of their importance in estimating internal dose. In particular, Kulp and Rivera have examined the effects of bone growth, rate of bone turnover, and the ratio of strontium to calcium in bone to that in diet, on the retention of ^{90}Sr in the skeleton of man.[21,22] The difference equation for the model developed by Kulp (herein referred to as the age dependent metabolic model) can be expressed as:

$$S_n = S_{n-1} - (f+\lambda)\, S_{n-1} + K_n \frac{I_n C_n}{G_n} \left[f_n Ca_{n-1} + (Ca_n - Ca_{n-1}) \right] \quad (13)$$

where

S_n = pc ^{90}Sr skeleton burden at time n

f_n = fractional bone turnover rate during the period from time n-1 to time n

TABLE 10

DOSE RECEIVED BY CRITICAL ORGANS OF MALES FROM DRINKING WATER[a]
(rem)

Age at Start of Exposure (yrs after birth)	Clinch River Water			Tennessee River Water		
	Skeleton	Total Body	Thyroid	Skeleton	Total Body	Thyroid
0	1.7	0.20	0.65	0.23	0.026	0.087
5	2.3	0.22	0.61	0.30	0.029	0.082
9	2.6	0.23	0.60	0.34	0.029	0.079
14	2.9	0.23	0.59	0.38	0.030	0.078
19	2.8	0.22	0.53	0.36	0.028	0.070
25	2.6	0.20	0.48	0.34	0.026	0.063
Standard Man	1.5	0.15	0.32	0.19	0.019	0.042
Maximum Permissible Dose[b]	60	10	60	20	1	20

[a]The cumulative dose for the period 1944 to 1963.

[b]According to recommendations of the ICRP Publication 2 where values of annual dose rate for continuous occupational exposure are reduced to 1/10 and applied to the Clinch River and reduced to 1/30 for skeleton and thyroid as critical organ and to 1/100 for whole body as critical organ and applied to the Tennessee River.

λ = ^{90}Sr radiological decay constant per period

$K = \left(\frac{Sr}{Ca}\right) \text{Bone} \Big/ \left(\frac{Sr}{Ca}\right) \text{Diet}$

I_n = fluid intake, liters/day

C_n = ^{90}Sr concentration in water, pc/liter

G_n = calcium intake, grams/day, and.

Ca_n = calcium content of the skeleton (grams).

The equation relates the loss and gain of ^{90}Sr during the period of interest, and is based on calcium metabolism. Calcium may enter and leave the skeleton each period. Bone turnover is defined as the quantity of calcium that enters and is excreted from the skeleton. The fractional bone turnover rate, F, is the bone turnover rate divided by the quantity of calcium contained in the skeleton. Strontium-90 in the skeleton is lost as a result of bone turnover and radiological decay and is gained by bone remodeling and bone growth.

By successive application of the difference equation, the skeletal burden can be determined. The dose rate is given by

$$Dn = a \frac{S_n}{W_n} \tag{14}$$

where

Dn = dose rate, rem/yr,

Wn = mass of the skeleton in kg at time n, and

a = a constant; for ^{90}Sr, 1.03×10^{-4} $\frac{\text{rems}}{\text{yr}} \Big/ \frac{\text{pc}}{\text{kg}}$.

These equations were coded for computer solution using an interval of one month during 0 to 2 years of age, three months during 2 to 24 years, and yearly intervals thereafter.

Estimation of the dose received by the skeleton of males due to ingestion of Clinch River water were performed using the same values for fluid intake, and ^{90}Sr concentration in water and skeleton mass, that were previously employed with the adjusted ICRP model in equations 8 and 10.[a]

[a]Calculations were performed by H. J. Fisher, U. S. Public Health Service, while working with the Internal Dose Estimation Section, Health Physics Division, ORNL.

Values of daily calcium intake and calcium content of the body were taken from Albritton and Mitchell, respectively;[14,23] values of bone turnover rate and the observed ratio (Kn) were from Rivera.[22] Examples of the cumulative skeletal dose (1944 to 1963) to individuals of various ages are given in Table 11. For comparative purposes, the table also includes the skeletal dose calculated with the adjusted ICRP model. In all cases the age dependent metabolic yields a slightly larger estimate of total dose (an average of 15% for the individuals listed) than the adjusted ICRP model. Unquestionably, changes can be expected in the values of metabolic factors as new information becomes available.

Dose Commitment Associated with Ingested Radionuclides

Dose commitments for the future (page 17) associated with the consumption of Clinch River and Tennessee River water are given in Table 12. These are estimated cumulative doses that persons of various ages receive, beginning in 1964 and extending to age 65; they result from the retention of radionuclides in critical organs due to ingestion of contaminated water during the period 1944 through 1963. For reasons previously enumerated, the critical organs of standard man have a smaller dose commitment (in general) than the organs of other individuals. In all cases the dose commitments are well below prescribed limits.

Exposures from Eating Contaminated Fish

Fish living in the Clinch River and Tennessee River downstream from White Oak Creek assimilate some of the radionuclides released to the river system. Since fish is a staple of man's diet, radionuclides present in the fish will contribute to his total dose.

Radionuclide Concentrations in Fish

The data on radionuclide concentrations in fish were obtained by the Subcommittee on Aquatic Biology, Clinch River Study Steering Committee.[24-29] Fish were collected during various seasons for the period of 1960 to 1962 and were processed to approximate, insofar as possible, normal human utilization.[25,29] Bottom feeders (carp, carpsucker, and buffalo) were processed either by grinding the flesh and bones together (total fish analyses) or by removing the flesh after cooking (flesh analyses). Sight

TABLE 11

DOSE RECEIVED BY SKELETON OF MALES FROM DRINKING WATER[a]

Age at Start of Exposure (yrs after birth)	(rem) Age Dependent Metabolic Model (Equations 13 and 14)	Adjusted ICRP Model (Equations 8 and 10)
0	2.2	1.7
5	2.4	2.3
9	3.1	2.6
14	3.3	2.9
19	3.3	2.8
25	2.9	2.6

[a]The cumulative dose from ingestion of Clinch River water during the period 1944 to 1963.

TABLE 12

DOSE COMMITMENT TO CRITICAL ORGANS OF MALES FROM DRINKING WATER[a]

(rem)

Age at Start	Clinch River Water			Tennessee River Water		
of Exposure	Skeleton	Total Body	Thyroid	Skeleton	Total Body	Thyroid
0	2.6	0.18	0.36	0.35	0.024	0.051
5	3.3	0.23	0.46	0.45	0.030	0.063
9	3.5	0.24	0.47	0.43	0.032	0.066
14	3.4	0.23	0.46	0.45	0.031	0.062
19	3.0	0.21	0.41	0.41	0.027	0.055
25	2.5	0.17	0.34	0.34	0.023	0.046
Standard Man	2.0	0.18	0.32	0.28	0.024	0.044

[a]The cumulative dose commitment beginning in 1964 and extending to age 65.

feeders (white crappie, bluegill, white bass, large mouth bass, sauger, and drum) were processed by removing the flesh after cooking. For the internal dose analysis, catfish were included with the sight feeders, since only the flesh of the catfish was processed. Another fish sampling program was completed May 1963. Carp, carpsucker, and buffalo were collected from the Clinch River and carp and buffalo were collected from the Tennessee River. The fish were pressure cooked and the flesh was separated from the bone for analysis.

Not all species of bottom feeders and sight feeders were collected in the sampling programs during 1960 to 1962. Therefore bottom feeders collected during 1960 to 1962 were considered as one sample; sight feeders were treated in similar manner. This evaluation of internal dose disregards any differences in fish due to the time of collection. Information on seasonal variation of such factors as feeding rates and water content of the flesh and their effect on radionuclide concentrations is unavailable and cannot be considered in the calculations.

Results of analyses of fish collected from the Clinch River and Tennessee River are listed in Tables 13 and 14, respectively. Average values are given for the principal radionuclides detected; analyses of the 1963 catch included only ^{90}Sr and ^{137}Cs. Variation of the averages is indicated by the standard error of the mean. Standard errors do not appear where fish were composited before analyses. Bottom feeders are listed by species, since information is available on the total quantities of these fish harvested commercially from Watts Bar Reservoir and from East Tennessee (Table 15). Information on sight feeders harvested is meager in comparison and does not warrant analyses by species. Only sport fishing takes place on the Clinch River.

Average values (for the same period) are observed to vary by factors ranging from about 2 to 5 between fish types from the same river; similar variations occur between fish of the same type but from the two rivers. A peculiar difference is noted in ^{90}Sr concentrations in sight feeders collected 1960-1962; the average concentration in Tennessee River fish is about 50% greater than in Clinch River fish. There is no explanation for this difference. Four carpsuckers, collected at Clinch River Mile 19.6, 90Sr

1963
90Sr (20) X 91 = 1820
(20) X 22 = 440
(20) X 43 = 860
~~20 X 43 = 860~~ (60) 3120
52 pCi/Kg
1.9 Bq/Kg

137Cs
(20) X 320 = 6400
(20) X 460 = 9200
(21) X 560 = 11760
61 | 27,360 | 448.5
16.6 Bq/Kg

106 Ru

TABLE 13

CONCENTRATION OF RADIONUCLIDES IN CLINCH RIVER FISH

(pc/kg fresh weight)

Fish Species	SAMPLE PERIOD	^{90}Sr Flesh	^{90}Sr Total[a]	^{137}Cs Flesh	^{137}Cs Total[a]	^{106}Ru Flesh	^{106}Ru Total[a]	^{60}Co Flesh	^{60}Co Total[a]
Carp	1960 - 1962	(17)[b] 500 ± 140	(40) 5100 ± 1700	(71) 510 ± 57	(39) 560 ± 79	(69) 170 ± 18	(39) 290 ± 78	(67) 66 ± 6.1	(39) 49 ± 9.9
	1963	(20) 91 ± 22	—	(20) 320 ± 110					
Carpsucker	1960 - 1962	(18) 540 ± 190	(39) 940 ± 120 (39) 4800[d]	(122) 1200 ± 460	(37) 640 ± 67	(22) 120 ± 30	(37) 56 ± 16	(22) 120 ± 19	(37) 32 ± 6.8
	1963	(20) 22 ± 4.4		(20) 460 ± 82					
Buffalo	1960 - 1962	(3) 240 ± 89	(30) 830 ± 110	(5) 480 ± 94	(30) 590 ± 92	(5) 110 ± 32	(30) 150 ± 38	(5) 78 ± 21	(30) 32 ± 6.8
	1963	(20) 43 ± 14		(21) 560 ± 84					
Sight Feeders[c]	1960 - 1962	(109) 180 ± 83		(126) 680 ± 120		(127) 120 ± 32		(127) 22 ± 11	

[a]Total fish consists of flesh and bone.

[b]Parenthetical values are numbers of fish analyzed.

[c]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, and drum; catfish also included.

[d]Includes four carpsuckers (composited) collected at CRM 19.6.

90Sr 1960-1962
Flesh Carp - 8500 (17)
Carpsucker - 9720 (18)
Buffalo - 720 (3)
Predator 19620 (109)
38560 | 147
262 pCi/g
9.7 Bq/kg

Total 204000 (40)
36,660 (39)
24,900 (30)
265,560 | 49

1960-1962
137Cs
36,210 (71) carp
146,400 (122) carpsucker
2,400 (5) Buffalo
85,680 (126) Predator
270,690 (324)
835.5 pCi/kg
30.9 Bq/kg

106 Ru
11,730 (69)
2,640 (22)
550 (5)
15,240 (127)
30,160 (223)
(135.2)
5 Bq/Kg

60Co (67)
4,422 (22)
2640 (5)
390 (127)
2794
10,246 | 221
46.7
3.1 Bq/Kg

90 Sr
(13)(120) = 1560
(10)(99) = 990
(24) 250 = 6000
8550 ÷ 171.9
6.7 Bq/Kg
4.7

(14) X 180 = 2520
(19) X 61 =
(10) X 130 = 1300
(24) X 170 = 4080
(48)
164.6
6.1 Bq/Kg

TABLE 14

CONCENTRATION OF RADIONUCLIDES IN FLESH OF

TENNESSEE RIVER FISH

(p c/kg Fresh Weight)

Fish Species	Sample Period	^{90}Sr	^{137}Cs	^{106}Ru	^{60}Co
Carp	1960-1962	(13)[a] 120 ± 33 1560	(14) 180 ± 55	(14) 80 ± 27	(14) 71 ± 17
	1963	(20) 5.1 ± .75	(19) 61 ± 17		
Carpsucker	1960-1962	(10) 99 ± 28 990	(10) 130 ± 27	(10) 69 ± 23	(10) 62 ± 18
Buffalo	1963	(20) 8.9 ± 2.9	(20) 73 ± 12		
Sight Feeders[b]	1960-1962	(24) 250 (6000) 56.6 (127.7) 4.7 Bq/Kg	(24) 170 4.5	(24) 48	(24) 66

[a]Parenthetical values are numbers of fish analyzed.

0.37 Bq/Kg

[b]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, and drum; catfish also included.

TABLE 15

COMMERCIAL FISH HARVEST FROM WATTS BAR RESERVOIR AND EAST TENNESSEE

(Pounds Fresh Weight)

Location	Carpsucker	Carp	Smallmouth Buffalo
Watts Bar Reservoir	15,600	23,700	161,000
East Tennessee	61,700	135,000	327,000
Fish Dilution Factor[a]	3.95	5.70	2.03

[a]Fish dilution factor = $\frac{\text{Pounds of East Tennessee Fish}}{\text{Pounds of Watts Bar Fish}}$

contained sufficient radioactivity to autoradiograph. This is typical of fish that have spent considerable time in White Oak Creek (or White Oak Lake).[30] Inclusion of these fish in the 1960-1962 analysis can be seen to increase significantly the average concentration of radionuclides. Although the concentrations of ^{90}Sr and ^{137}Cs in fish flesh during 1963 are found to be less than that observed during the period 1960 to 1962, a "t" test showed that only ^{90}Sr in carp and carpsucker and ^{137}Cs in carp are significantly different at the 5% level. These smaller concentrations of ^{90}Sr and ^{137}Cs in fish flesh are attributed to the reduction of radionuclide release to the Clinch River. Not to be overlooked is the fact that fallout from nuclear tests contributes about 45% of ^{90}Sr and 20% of ^{137}Cs to the total load in the Clinch River during 1962 and 1963.

Estimated Intake of Radionuclides from Fish

An estimate is made of man's intake of radionuclides (including radioactive fallout) by assuming an annual rate of fish consumption of 37 lb.[31] This rate of fish consumption applies to commercial fishermen and, as a result, the estimate of intake is for an admittedly high exposure group. Data on the quantity of specific types of fish consumed are not available. A recent survey of 80 fishermen by the Tennessee Fish and Game Commission (completed August 1964) reports that fish are consumed with one meal each week. None of those interviewed prepare the total fish (flesh plus bone) for eating.

54 lbs Calculations made are based on an annual consumption of 37 lb of bottom feeders, considering both the total fish and the flesh, and consumption of 37 lb of sight feeders, considering only the flesh. The fraction of the various species of bottom feeders caught is assumed to be distributed according to commercial harvests from Watts Bar Reservoir. Estimates of the annual intake of specific radionuclides by consuming Clinch River or Tennessee River fish are given in Table 16 and 17, respectively. A very noticeable increase in ^{90}Sr intake is observed when consumption of bottom feeders (total fish) is considered. This significantly larger intake is due to the concentration of ^{90}Sr by the bones of the fish, all of which are assumed to be eaten. The assumption that 37 lb of total fish are consumed each year is certainly conservative. However, without better

data on fish consumption, it is impossible to arrive at a more reasonable value of intake.

Radionuclide intake by the general population is likely to be influenced from dilution by other fish harvested in East Tennessee, as well as by differences in radionuclide content among species of bottom feeders. Applying a fish dilution factor (bottom feeders) for East Tennessee fish (Table 15), gives the revised annual intakes shown in Tables 16 and 17. A significant decrease in radionculide intake is observed, the reduction factors ranging from about 2 to 4. Fish collected from the Clinch River or the Tennessee River and shipped outside the East Tennessee area are likely to be diluted even more with fish from other parts of the country.

Relation to Permissible Intake for Man.- A maximum permissible intake (MPI) is estimated by assuming a daily intake of 2.2 liters of water containing the maximum permissible concentration (MPC) of the radionuclide of interest. Using the estimated intakes (Tables 16 and 17), it is possible to calculate the fraction of MPI attained as a result of eating contaminated fish (Tables 18 and 19). The estimates indicate that bone of the highest exposure group receive the largest dose; on the average, 7.0 to 8.6% of the MPI is attained as a result of consuming bottom feeders (total fish) from the Clinch River. Strontium-90 is responsible essentially for the total bone dose. If only the flesh of bottom feeders is consumed, the percentage of MPI attained is reduced to 1.5%. As shown, further reduction in dose is likely due to dilution with other East Tennessee fish. The estimated percentage of MPI attained during 1963 is less than 1% for the critical organs, bone, total body, GI tract, and thyroid.

More information would be required to estimate the intake of radionuclides due to past events. Such information would include: (1) rate of transfer of radionuclides from water to fish (flesh and bone) as a function of radionculide and stable element concentration, fish age, and season of the year: (2) rate of transfer of radionuclide from bone to flesh while cooking and method of fish preparation; and (3) type and quantity of fish consumed and fish eating habits of individuals as a

TABLE 16

ESTIMATED ANNUAL INTAKE OF RADIONUCLIDES BY ASSUMED CONSUMPTION OF CLINCH RIVER FISH[a]

(nc/year)

Fish	Sample	^{90}Sr		^{137}Cs		^{106}Ru		^{60}Co	
Species	Period	Flesh	Total[b]	Flesh	Total[b]	Flesh	Total[b]	Flesh	Total[b]
Bottom Feeders[c]	1960-1962	4.9±1.3	23±3.7 (28)[f]	9.0±1.4	10±1.3	2.0±0.44	2.7±0.54	1.3±0.28	0.58±0.94
Bottom Feeders[c]	1963	0.78±0.19		8.8±1.2					
Bottom Feeders[d]	1960-1962	1.9±0.60	7.6±0.83 (8.9)	3.7±0.64	4.4±0.19	0.81±0.21	1.1±0.25	0.58±0.44	0.24±0.061
Bottom Feeders[d]	1963	0.32±0.091		3.9±0.56					
Sight Feeders[e]	1960-1962	3.0±1.4		11±2.6		2.0±0.54		0.38±0.19	

[a]Calculated from the concentration of the radionuclide found in either bottom feeder flesh, bottom feeder total fish, or sight feeder flesh, and an assumed consumption of 37 lbs per year of each category. Thus, these calculated intakes are not additive.

[b]Total fish consists of flesh and bone.

[c]Bottom feeders include carp, carpsucker, and buffalo.

[d]Intake adjusted by fish dilution factor.

[e]Sight feeders include white crappie, blue gill, white bass, largemouth bass, sauger, and drum; catfish also included.

[f]Parenthetical values include four carpsuckers (composited) collected at CRM 19.6.

TABLE 17

ESTIMATED ANNUAL INTAKE OF RADIONUCLIDES BY ASSUMED CONSUMPTION OF FLESH OF TENNESSEE RIVER FISH[a]
(nc/year)

Fish Species	Sample Period	^{90}Sr	^{137}Cs	^{106}Ru	^{60}Co
Bottom Feeders[b]	1960-1962	1.9 ∓ 0.38	2.7 ∓ 0.59	1.3 ∓ 0.31	1.1 ∓ 0.21
Bottom Feeders[c]	1963	0.14 ∓ 0.042	1.2 ∓ 0.18		
Bottom Feeders[d]	1960-1962	0.39 ∓ 0.075	0.53 ∓ 0.11	0.26 ∓ 0.062	0.23 ∓ 0.043
Bottom Feeders[d]	1963	0.066 ∓ 0.021	0.55 ∓ 0.085		
Sight Feeders[e]	1960-1962	4.3	2.8	0.81	1.1

[a]Calculated from the concentration of the radionuclide found in either bottom feeder flesh or sight feeders flesh and an assumed consumption of 37 lbs per year of each category. Thus, these calculated intakes are not additive.

[b]Bottom Feeders include carp and carpsucker.

[c]Bottom Feeders include carp and buffalo.

[d]Intake adjusted by Fish Dilution Factor.

[e]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, and drum; catfish also included.

TABLE 18

ESTIMATED PERCENTAGE OF MPI THAT MAN MAY ATTAIN BY CONSUMING CLINCH RIVER FISH[a]

Fish Species	Sample Time	Critical Organ			
		Bone	Total Body	GITract	Thyroid
Bottom Feeders[b] (flesh)	1960-1962	1.5±0.39	0.87±0.23	0.072±0.0081	0.38±0.072
Bottom Feeders[b] (flesh)	1963	0.27±0.059	0.19±0.034	0.030±0.0035	0.060±0.010
Bottom Feeders[b] (total[c])	1960-1962	7.0±1.1 (8.6)[f]	4.1±0.66 (5.0)	0.14±0.014 (0.15)	1.4±0.19 (1.6)
Bottom Feeders[d] (flesh)	1960-1962	0.60±0.19	0.36±0.11	0.03±0.0039	0.16±0.034
Bottom Feeders (flesh)[d]	1963	0.11±0.028	0.081±0.016	0.013±0.0018	0.024±0.0049
Bottom Feeders[d] (total)	1960-1962	2.4±0.28 (2.9)[f]	1.4±0.19 (1.7)	0.053±0.0047 (0.0058)	0.48±0.051 (0.57)
Sight Feeders[e] (flesh)	1960-1962	0.94±0.43	0.61±0.25	0.071±0.012	0.31±0.080

[a]The ratio of the estimated annual intake of radionuclides from consuming the particular category of fish to the maximum permissible intake (MPI) for the critical organ of interest. Thus these calculated percentages of MPI are not additive.

[b]Bottom feeders include carp, carpsucker, and buffalo.

[c]Total fish consist of flesh and bone.

[d]Intake adjusted by Fish Dilution Factor.

[e]Sight Feeders include white crappie, bluegill, white bass, largemouth bass, sauger, and drum; catfish also included.

[f]Parenthetical values include four carpsuckers (composited) collected at CRM 19.6.

TABLE 19

ESTIMATED PERCENTAGE OF MPI THAT MAN MAY ATTAIN BY CONSUMING FLESH OF TENNESSEE RIVER FISH[a]

Fish Species	Sample Period	Critical Organ			
		Bone	Total Body	GI Tract	Thyroid
Bottom Feeders[b]	1960-1962	1.8 ∓ 0.36	3.7 ∓ 0.68	0.11 ∓ 0.014	0.55 ∓ 0.084
Bottom Feeders[c]	1963	0.14 ∓ 0.039	0.33 ∓ 0.075	0.012 ∓ 0.0020	0.029 ∓ 0.0066
Bottom Feeders[d]	1960-1962	0.37 ∓ 0.071	0.69 ∓ 0.14	0.021 ∓ 0.0026	0.11 ∓ 0.017
Bottom Feeders[d]	1963	0.066 ∓ 0.019	0.15 ∓ 0.037	0.0057 ∓ 0.00082	0.013 ∓ 0.0035
Sight Feeders[e]	1960-1962	4.0	7.6	0.11	0.83

[a]The ratio of the estimated annual intake of radionuclides from consuming the particular category of fish to the maximum permissible intake (MPI) for the critical organ of interest. Thus, these calculated percentages of MPI are not additive.

[b]Bottom feeders include carp and carpsucker.

[c]Bottom feeders including carp and buffalo.

[d]Intake adjusted by Fish Dilution Factor

[e]Sight feeders include white crappie, bluegill, white bass, largemouth bass, sauger, and drum; catfish also included.

function of age. Current research suggests that the concentration of ^{90}Sr in the flesh of white crappie rapidly reaches equilibrium with the water.[32] Such information helps to answer, in part, the questions raised by (1) above and an extension of such studies will enhance the estimates of dose to man by this path of intake.

An interesting calculation was made based on the ^{90}Sr content of the four carpsuckers previously mentioned. The combined weight of flesh and of whole fish (flesh and bone) for the four carpsuckers was 0.51 kg and 0.85 kg, respectively; the ^{90}Sr concentration in flesh was 500 pc/kg and in whole fish was 43000 pc/kg. An individual eating the four fish could have attained 0.1% of MPI (bone) from the flesh and 11% of MPI from the whole fish. Although such an event is unlikely, it indicates the possibility that consumption of relatively few fish (flesh and bone) could lead to a significant exposure.

Computer Calculations of Internal Dose

The dose received by the skeleton, total body, and thyroid of man, due to consumption of contaminated water and fish, is calculated by use of the models described in the section, "Estimation of Radiation Dose Following Ingestion of Contaminated Water". In addition to the assumptions listed for contaminated drinking water, it is also assumed that 37 lb per year of the flesh of bottom feeders is consumed by a standard man during the period 1960 to 1963. Without information on actual fish consumption as a function of age, it is further assumed that the intake of fish is distributed as the intake of water. Another way to state this assumption is that the ratio of fish eaten by an individual to that of standard man is equal to the ratio of water consumed by the individual to that of standard man.

Figure 9 shows the computed annual dose to the skeleton due to consumption of contaminated water and fish. By comparison with Figure 6 it is seen that the net increase in dose rate to the skeleton is small. This is due to the fact that data for only four years of fish collection (1960-1963) is available for the calculations, to the long effective half life of the critical radionuclide, ^{90}Sr and to the reduction in ^{90}Sr released to the river. The net increase in total dose received through

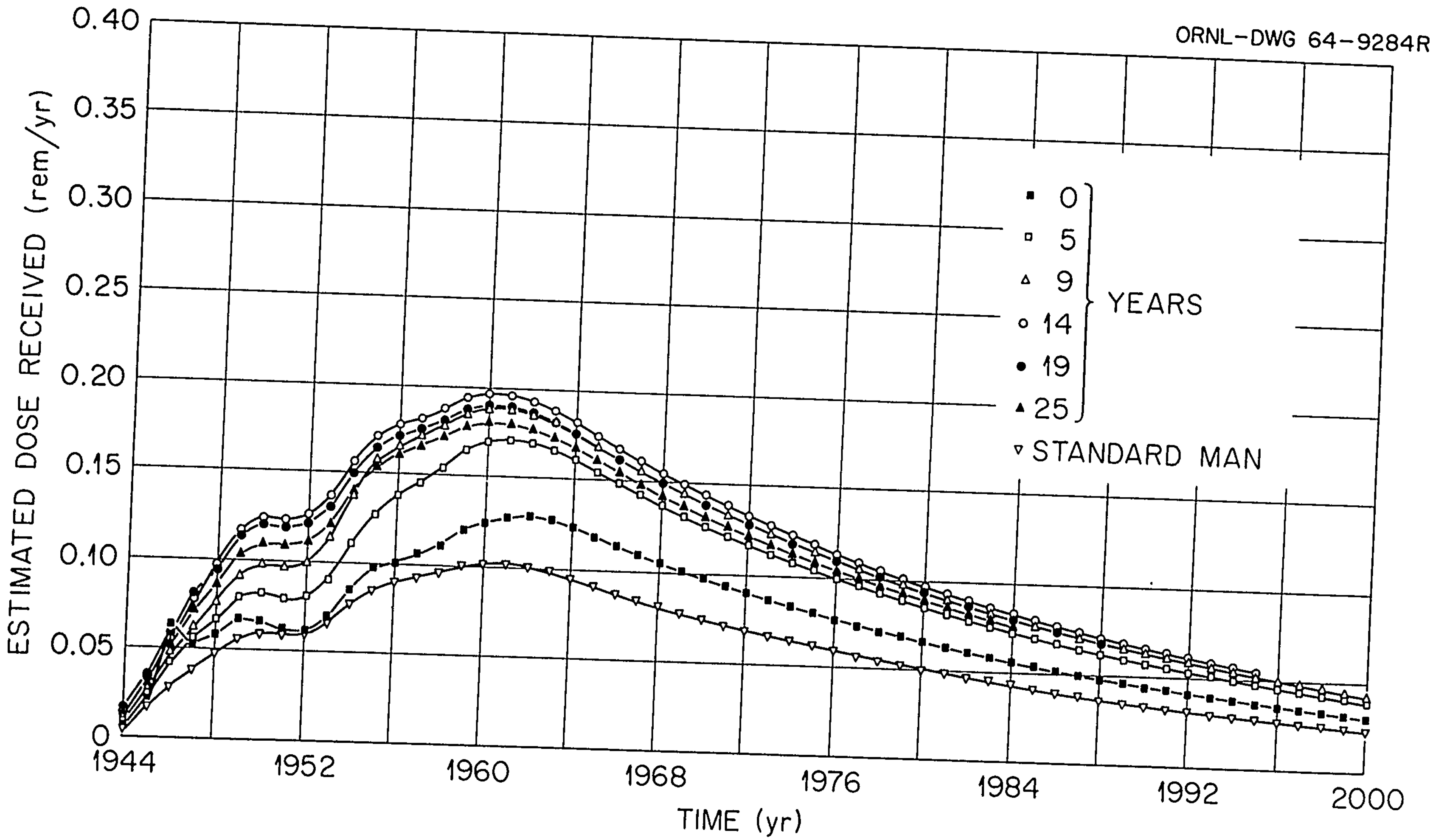


Fig. 9. Estimated Dose Received by Skeleton of Males from Drinking Clinch River Water and Consuming Contaminated Fish.

1963 by the organs of interest is given in Table 20. The cumulative dose over the 4-year exposure period is not excessive, with the skeleton receiving the largest increase of about 30 mrad. Consumption of total fish could result in an increase of the cumulative dose by a factor of 5 to 10, but available information does not justify such an assumption.

Exposures from External Sources

Radionuclides in Water Treatment Plants

The presence of radionuclides in raw water entering a water treatment plant may lead to their concentration in the plant and create an external or internal dose problem. Three water systems using Clinch River water as a source of supply were investigated. The Oak Ridge Water Plant has its raw water intake at CRM 41.5, well above the outfall of White Oak Creek. The other two water treatment plants - serving the Oak Ridge Gaseous Diffusion Plant (ORGDP) and the Kingston Steam Plant - have water intakes at CRM 14.5 and on the Emory River near CRM 4.4, respectively. These water treatment plants are basically similar in design. The treatment processes include: prechlorination for algae control; coagulation using alum, soda ash (as dictated by raw water alkalinity), and occasionally coagulant aids for turbidity removal; settling; filtration (either sand or anthracite media); and postchlorination for disinfection. Activated carbon is used when taste and odor problems occur. Water used in boilers is treated further by zeolite softeners.

The investigation consisted of: external radiation surveys, using a scintillation-type survey meter (calibrated with radium); collection and analysis of samples of sludge from settling basins, condensers, hot water heaters, boilers, air conditioners, and an elevated tank; collection and analysis of samples of sediment from filters and cores of filter media; and collection and analysis of samples of zeolite softener regenerant, as well as the softener media.

At the time of the surveys, various amounts of water had been treated since the last time settling basins had been cleaned or filters backwashed (Table 21). Thus, there was variation in the amount of accumulated sludge in the settling basins and sediment on the filters. Results of the external radiation survey are summarized in Table 22. Generally there was little

TABLE 20

DOSE RECEIVED BY CRITICAL ORGANS OF MALES FROM CONSUMING FISH[a]
(rem)

Age at Start of Exposure - 1944	Clinch River Water			Tennessee River Water		
	Skeleton	Total Body	Thyroid	Skeleton	Total Body	Thyroid
0	0.033	0.0035	0.011	0.013	0.0014	0.0037
5	0.031	0.0032	0.0089	0.012	0.0012	0.0031
9	0.028	0.0029	0.0078	0.011	0.0011	0.0027
14	0.030	0.0026	0.0072	0.011	0.0011	0.0025
19	0.027	0.0026	0.0069	0.011	0.0010	0.0024
25	0.026	0.0025	0.0066	0.010	0.0010	0.0023
Standard Man	0.015	0.0021	0.0047	0.006	0.0008	0.0016

[a]The cumulative dose for the period 1960-1963.

TABLE 21

OPERATIONAL DATA OF WATER TREATMENT PLANTS

System	Volume Through[a] Flocculator and Settling Basin (gal)	Volume Through[a] Filter (gal)	Sludge in Settling Basin (cu ft)	Plant Capacity (gal/day)
Oak Ridge Water Plant	1.1×10^9	1.8×10^6	2×10^4	22×10^6
ORGDP	5.4×10^8	4.5×10^6	6×10^3	4×10^6
Kingston Steam Plant	1.9×10^6	3.7×10^5		5.7×10^5

[a]Volume through flocculator, settling basin, and filter since last cleaned.

TABLE 22

MEASUREMENTS OF IONIZING RADIATION IN WATER TREATMENT PLANTS

(mr/hr)

System	Ground Surface	Flocculator	Settling Basin	6 in. Above Water in Settling Basin	Filter
Oak Ridge Water Plant	0.016	0.013	0.012	0.0097	0.0095
ORGDP	0.017	0.011	0.012	0.0092	0.0092
Kingston Steam Plant	0.015	0.0083	0.0087		0.015

[a] All measurements (except as noted) were made 3 ft above walking surface of the particular component of the treatment plant.

difference in the dose rates at different units of the plants. Dose rates above background levels (the Oak Ridge Water Treatment Plant was considered as background) were, with one exception, not found. At a distance of 2 in. above a partially drained filter at the Kingston Steam Plant, a dose rate of 0.021 mr/hr was measured. The dose rate remained the same after the filter was backwashed. It is likely that the anthracite media of the filter to some extent concentrates radionuclides by sorption. The dose rate above these filters (0.015 mr/hr) was also influenced by the natural radioactivity present in block used for construction of the building. External exposure to radioactive materials concentrated in these water treatment plants was not significantly different from exposure to background radiation.

Immersion in Contaminated Water

Due to the presence of radionuclides, the river will act as a source of radiation to persons engaged in swimming, boating, fishing, and water skiing. Since direct measurements of immersion dose rate were unavailable, it was necessary to estimate the dose rate by considering the radionuclide composition of the water.

The immersion dose calculation assumes the body is in the center of a sphere and receives equal quantities of radiation from all directions. The external exposure from beta radiation may be written in units of rad per day:[33]

$$\text{Beta Dose Rate} = \frac{3.7 \times 10^4 \frac{\text{dis/sec}}{\mu\text{c}} \times 8.64 \times 10^4 \frac{\text{sec}}{\text{day}} \times Q \frac{\mu\text{c}}{\text{g}} \times a x b x E_m \times 10^6 \frac{\text{ev}}{\text{Mev}} \times P_t}{6.25 \times 10^{13} \frac{\text{ev}}{\text{g-rad}} \times P_m \times N} \qquad (15)$$

where

$Q = \mu c/g$ of water

a = factor introduced in case the radius of beta emitting medium is less than the maximum range of the beta ray,

$b = \frac{E_{avg}}{E_m}$,

P_t = relative mass stopping powerof tissue,

P_m = relative mass stopping power of water,

$N = \frac{\text{ev/ion pair}}{32.5}$,

E_m = maximum energy of type considered, and

E_{avg} = average energy of type considered.

Assuming that a = 1, N = 1, $P_t = P_m$, and $E_{avg} = E_i$ (effective absorbed energy per disintegration), the expression is simplified to:

$$\text{Beta Dose Rate} = 51.2\ QE_i \tag{16}$$

An empirical formula was used to estimate the average effective absorbed energy of a beta disintegration.[1]

$$E_i = 0.33\ E_m\ f \left(1 - \frac{\sqrt{z}}{50}\right) \left(1 + \frac{\sqrt{E_m}}{4}\right) \tag{17}$$

where

f = fraction of disintegration at a particular energy,

z = atomic number

The penetration distance in water of the most energetic beta particles from the radionuclides involved is about one centimeter. Therefore, the beta radiation at the surface of a body immersed in the contaminated water is effectively one-half of that calculated by equation 16.

Similarly, the external exposure from gamma radiation may be written in units of rad per day:[33]

$$\text{Gamma Dose Rate} = \frac{51.2\ Q\ E\ Pt\ (\mu - \sigma_s)_m (1-e^{-\mu_\ell r})}{P_m\ \mu_\ell} \qquad (18)$$

where

μ = total absorption coefficient,

σ_s = Compton scattering coefficient,

μ_ℓ = $(\mu - \sigma s)_m$ plus the fraction of σ_s representing the scattered and degraded radiation that reaches the point of measurement,

r = radius of contaminated medium,

$E = E_m\ f(1-e^{-\sigma x})$ (from ICRP 1959),

σ = total absorption coefficient less Compton scattering coefficient in body organ for the given photon energy,

x = effective radius of body organ.

Assuming that $P_t = P_m, \mu_\ell = (\mu - \sigma s)_m$, $r = \infty$, σx is large, and that the submerged body is receiving radiation from 4 π steradians, the expression becomes:

$$\text{Gamma Dose Rate} = 51.2\ QE_m f \qquad (19)$$

In each instance where some latitude is allowed in the assumptions, a conservative approach was taken. Therefore the computed dose rates are judged to be conservative.

Where the water contains a mixture of radionuclides, it is necessary to calculate the dose rate from each radionuclide. The total dose rate is then the sum of the individual dose rates. Decay schemes presented by Blomeke and Todd were used in the calculations.[34] To simplify calculations, the dose rate of each radionuclide was normalized for a concentration of one μ c per ml (Table 23). Tabulated values are one-half the beta dose rate (equation 16) and the total gamma dose rate (equation 19).

The immersion dose rates due to beta and gamma radiation at the two stations are listed in Table 24 and shown graphically in Fig. 10 for CRM 14.5. The total dose rate at CRM 14.5 and TRM 465.5 is shown in Fig. 11.

TABLE 23

IMMERSION DOSE RATE OF RADIONUCLIDES

(rad/day per $\mu c/ml$)

Nuclide	Beta	Gamma	Total	Parent Plus Daughter
Co^{60}	2.90	128	131	131
Sr^{90}	5.4	0	5.4	
Y^{90}	22.1	0.29	22.4	27.8
Cs^{137}	4.97	0	4.97	
Ba^{137}	0	33.8	33.8	38.8
Ru^{106}	0.30	0	0.30	
Rh^{106}	33.6	12.6	46.2	46.5
Zr^{95}	3.25	36.0	39.3	39.3
Nb^{95}	0.13	38.1	38.2	38.2
Ce^{144}	2.11	2.06	4.17	
Pr^{144}	29.6	4.06	33.7	37.9
Y^{91}	14.9	0.19	15.1	15.1
I^{131}	4.93	19.7	24.6	24.6

TABLE 24

IMMERSION DOSE RATES IN CLINCH AND TENNESSEE RIVERS

(units of 10^{-4} mrad/24-hr Exposure)

Year	Clinch River Mi 14.5			Tennessee River Mi 465.5		
	Beta	Gamma	Total	Beta	Gamma	Total
1949	19	16	35	2.4	2.0	4.4
1950	3.4	5.2	8.6	0.5	0.79	1.3
1951	2.7	2.1	4.8	0.46	0.35	0.81
1952	8	5.0	13	1.3	0.77	2.1
1953	13	2.7	16	2.0	0.41	2.4
1954	20	7.2	27	2.3	0.82	3.1
1955	18	9.9	28	2.8	1.6	4.4
1956	16	18	34	2.6	2.9	5.5
1957	10	9.9	20	1.4	1.4	2.8
1958	16	8.4	24	3.1	1.6	4.7
1959	71	67	140	8.5	8.0	17
1960	170	95	270	25	14	39
1961	160	79	240	21	10	31
1962	89	38	120	12	5.2	17
1963	33	17	50	4.6	2.3	6.9

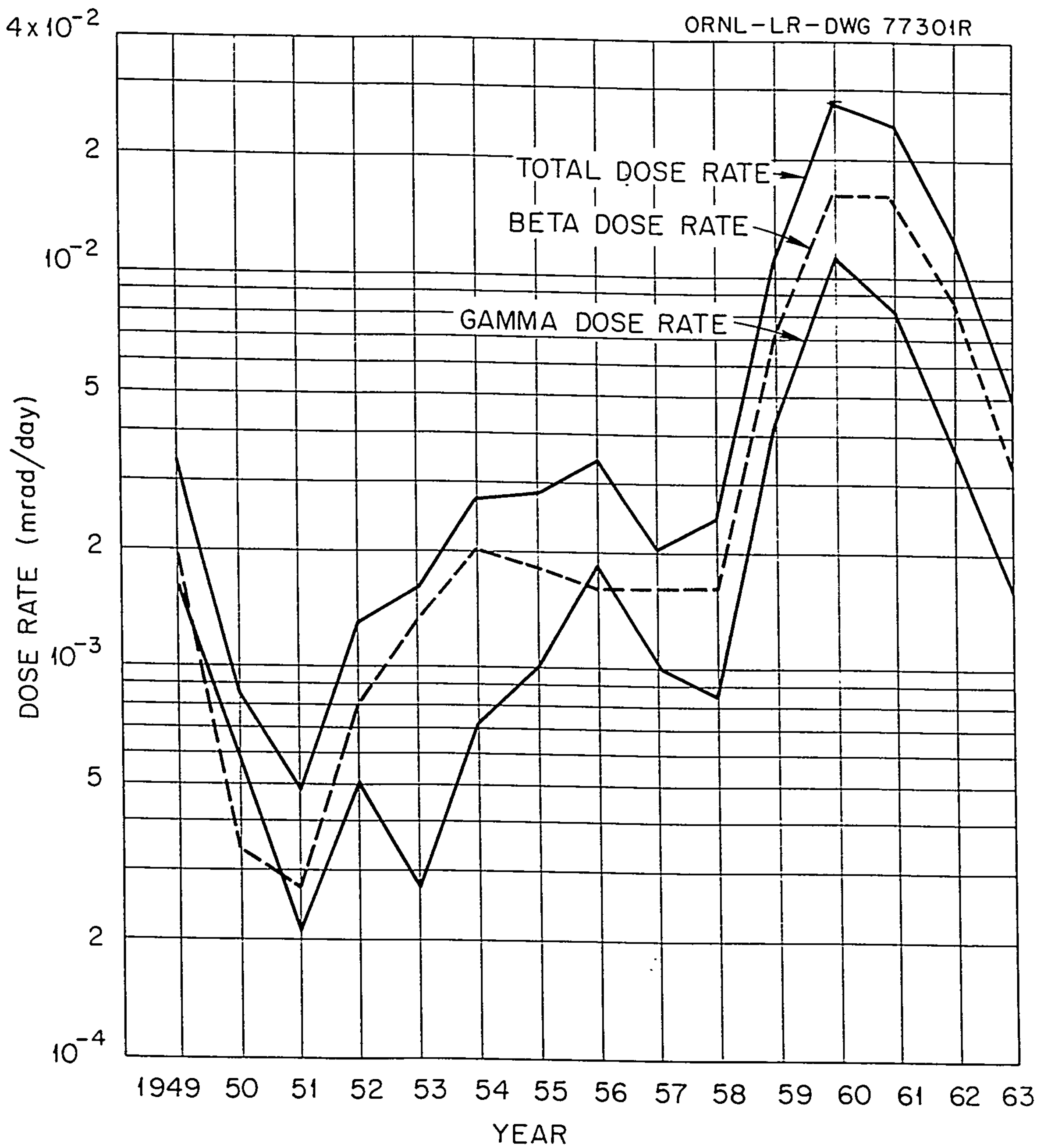


Figure 10. Immersion Dose Rate at CRM 14.5

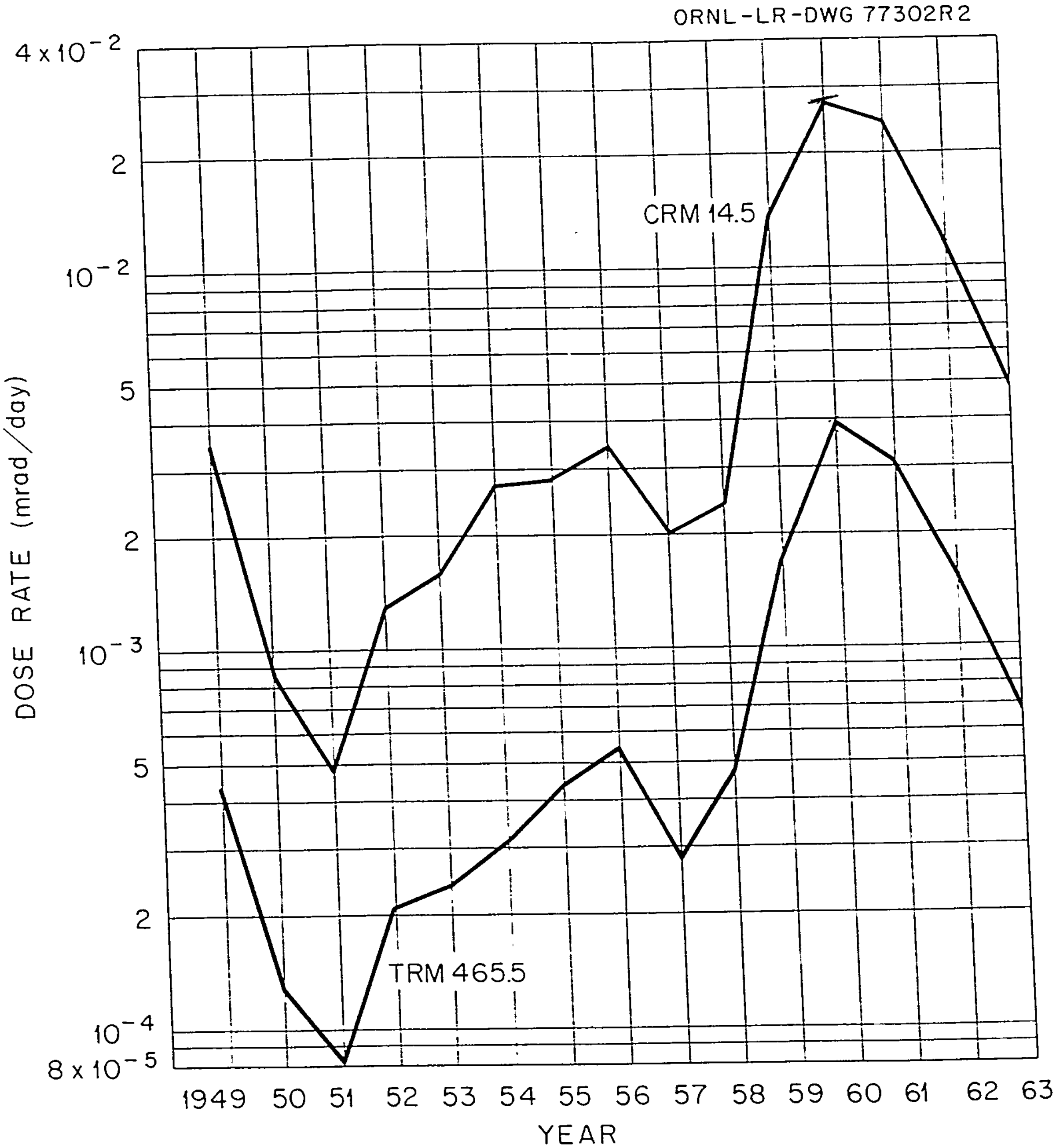


Fig. 11. Total Immersion Dose Rate at CRM 14.5 and TRM 465.5

A maximum dose rate of 0.027 mrad per day of exposure at CRM 14.5 (1960) is estimated. The dose rate is a function of nuclide type and concentration. Until 1958, the largest fraction of beta dose was associated with ^{90}Sr and the largest gamma dose was generally due to ^{137}Cs. Since then, ^{106}Ru has accounted for about 75% of the total immersion dose.

Contaminated Bottom Sediments

Radionuclides associated with solids that have settled to the bottom of the river can be expected to contribute to the total dose received by man. Although earlier calculations assumed complete dilution of fission products in the river, annual surveys made by the ORNL Applied Health Physics Section show that some of the radionuclides are retained by the bottom sediments.[35]

Radionuclide Concentrations in Sediments.-- Measurements were made at cross sections 2 miles apart in the Clinch River and at 50-ft intervals across the river at each cross section. In the Tennessee River and TVA Reservoirs, measurements were made at sections approximately 10 miles apart and at 10 points at each station. Measurements consisted of gamma counts obtained with a multiple-GM-tube detector ("Flounder"), lowered to the surface of the bottom sediments, and analysis of the mud samples taken at each measurement point. Average concentrations of specific radionuclides in bottom sediments were calculated by averaging all values for the entire reach of the lower Clinch River and of the Tennessee River (Table 25). Cesium-137, ^{144}Ce, ^{60}Co, and ^{106}Ru, were found to be the principal radionuclides associated with these sediments. Reasons for such selectivity are enumerated elsewhere.[36] The values listed as ^{91}Y are not measured but, as mentioned earlier, are calculated as the difference between concentrations of trivalent rare earths and ^{90}Sr. The reasons for large changes in concentrations of ^{137}Cs and ^{106}Ru in sediments have already been discussed.

The "Flounder" is used principally to furnish qualitative information on the build-up of gamma emitting radionuclides in bottom sediments. Construction of the device makes it insensitive to beta radiation. Although the "Flounder" is calibrated routinely with a sealed radium source, the complex spectrum of gamma rays from both the contaminated sediments

TABLE 25

AVERAGE CONCENTRATION OF RADIONUCLIDES IN BOTTOM SEDIMENTS[a]

Nuclide	1954	1955	1956	1957	1958	1959	1960	1961
				CLINCH RIVER				
Cs^{137}	20	25	200	210	160	280	170	81 - 2997
Sr^{90}	3.6	3.8	6.0	4.1	5.9	5.4	2.4	0.85 31.45
Ce^{144}	6.1	24	41	12	22	38	19	6.9
Y^{91}	0.8	5.9	7.8	1.5	6.8	83	79	20
Ru^{106}	4.5	4.8	8.1	5.6	8.6	12	70	130 4810
Co^{60}	19	21	42	15	12	33	19	11
				TENNESSEE RIVER				
Cs^{137}	6.6	6.7	35	32	21	17	18	14
Sr^{90}	2.4	0.3	2.5	0.76	1.4	0.8	0.5	0.41 15.17
Ce^{144}	1.6	11	8.3	2.7	6.6	4.5	1.6	1.5
Y^{91}	0	5.9	1.2	0.84	4.3	4.3	5.6	2.8
Ru^{106}	1.5	2.7	3.0	2.3	3.5	4.6	15	23
Co^{60}	5.8	8.0	7.0	3.6	3.3	3.7	3.2	2.4

[a] 10^{-6} μ c/gram DRIED SEDIMENT.

X 37

and the radium source prevents a direct determination of exposure dose by use of this instrument. Estimates of exposure dose can be made (Tables 26 and 27) but it is necessary to recognize their limitations. Figure 12 shows the average gamma counting rate in the Clinch River and Tennessee River, as determined by the "Flounder" and averaged for the entire study reach of each, and the curies per year of ^{137}Cs and ^{60}Co released. In general, measurements in the Clinch River reflect the quantity of ^{137}Cs and ^{60}Co released each year. Maximum readings in the Clinch River (generally at CRM 8.3) were larger than the average readings by a factor of 1.9 ± 0.09; similarly, this ratio in the Tennessee River was 1.8 ± 0.2.

Estimation of Radiation Dose from Sediments. - For the purpose of estimating the radiation dose, it was assumed that the average radionuclide composition of the sediments was uniformly distributed in an infinite source. Further, it was assumed that the individual would be exposed to one-half the submersion dose of beta particles and gamma photons (i.e., from one-half a sphere). Such an assumption is reasonable, since the exposed individual is likely to be standing on or floating above the contaminated sediments. Normally, only the feet would be subjected to the total beta dose rate and some fraction greater than one-half of the gamma dose rate.

Estimated dose rates from bottom sediments in the Clinch River and Tennessee River are listed in Tables 26 and 27. The beta dose rate was taken as one-half the value determined by use of equation 16 and the gamma dose rate by use of one-half the calculated value of equation 19. Since the source is not infinite in extent, the calculated values of gamma dose rate are overestimates. Accordingly, the highest dose rate of 12 mrad per day occurred in 1959, and was divided as 40% beta and 60% gamma radiation. The percentage contributions of specific radionuclides to the beta and gamma dose rates are listed in Table 28. The total rare earths, ^{137}Cs, and ^{106}Ru are the principal contributors to beta dose rates, and ^{60}Co and ^{137}Cs account for the largest fraction of gamma dose rate.

TABLE 26

ESTIMATED RADIATION DOSE RATES FROM CONTAMINATED SEDIMENTS IN CLINCH RIVER

	Measured[a] (10^{-2} mr/24-hr)		Calculated (10^{-2} mrad/24-hr exposure)			
Year	Average	Maximum	Beta	1/2 Gamma[c]	Total	Attenuated[b] 1/2 Gamma[c]
1951	39			90[d]		
1952	88			320[d]		
1953	53			160[d]		
1954	57	110	60	160	220	9.5
1955	60	110	130	180	310	11
1956	130	260	300	630	930	35
1957	96	180	180	460	640	24
1958	100	200	210	360	570	19
1959	160	280	450	710	1160	39
1960	150	280	510	460	970	25
1961	95	170	530	290	820	15

[a]In units of 10^{-2} mr/24-hr exposure as measured by the "Flounder."

[b]Attenuation through 3 ft of water.

[c]One-half of total gamma dose from infinite source.

[d]Estimated from correlation relationship.

TABLE 27

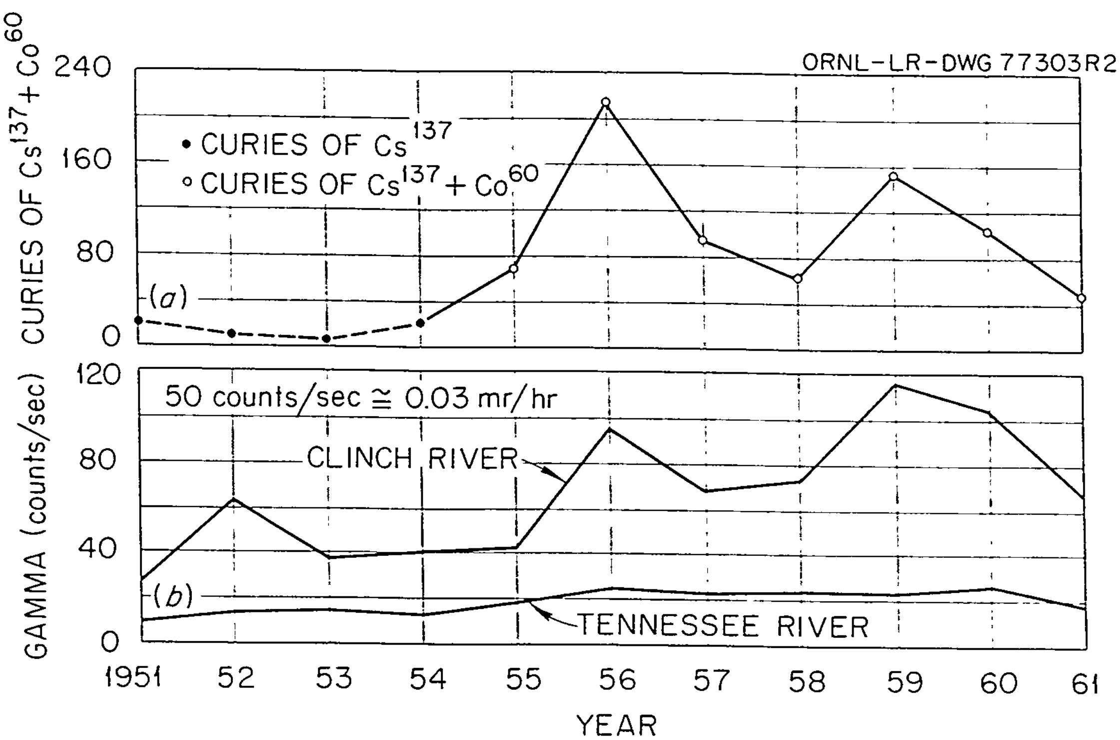
ESTIMATED RADIATION DOSE RATES FROM CONTAMINATED SEDIMENTS IN TENNESSEE RIVER

	Measured[a] (10^{-2} mr/24-hr)		Calculated (10^{-2} mrad/24-hr exposure)			
Year	Average	Maximum	Beta	1/2 Gamma[c]	Total	Attenuated[b] 1/2 Gamma[c]
1951	13					
1952	22					
1953	23					
1954	19	30	22	50	72	3.0
1955	26	43	60	68	128	4.2
1956	36	69	65	110	175	6.1
1957	33	58	37	80	117	4.2
1958	35	63	55	62	117	3.5
1959	30	63	48	56	104	3.1
1960	33	49	75	61	136	3.3
1961	26	48	95	54	149	2.8

[a]In units of 10^{-2} mr/24-hr exposure as measured by the "Flounder."

[b]Attenuation through 3 ft of water.

[c]One-half of total gamma dose from infinite source.



(a) CURIES OF Cs^{137} AND Co^{60} RELEASED TO CLINCH RIVER

(b) AVERAGE GAMMA COUNT AT SURFACE OF BOTTOM SEDIMENTS

Fig. 12. Comparison of Gamma Radiation from Bottom Sediments with Release of Cs^{137} and Co^{60} in Waste.

TABLE 28

PERCENTAGE CONTRIBUTION TO BOTTOM SEDIMENT DOSE RATE BY RADIONUCLIDES

Type of Radiation	Nuclide	CLINCH RIVER		TENNESSEE RIVER	
		1954-1959	1960-1961	1954-1959	1960-1961
Beta	TRE[a]	50	23	52	15
	Ru^{106}	14	64	22	75
	Cs^{137}	31	13	21	10
Gamma	Co^{60}	44	25	50	31
	Cs^{137}	53	55	45	47
	Ru^{106}	1	14	3	22

[a]TOTAL RARE EARTHS

An estimate can be made of the bottom sediment gamma dose rate in the Clinch River for periods when only "Flounder" measurements were made. This made possible by the apparent relationship between "Flounder" measurements and calculated gamma dose rates, and is expressed as a coefficient of correlation of 0.90. With "Flounder" measurements X as abcissa and gamma dose rates Y as ordinates, the relationship is given by the equation $Y = -0.84 + 4.64 X$. The 95% confidence limits of the slope of the regression curve are ± 2.31. The correlation coefficient for similar data from the Tennessee River is 0.58, and the slope of the regression curve and its 95% confidence limits is 0.19 ± 3.45. Thus, estimates of bottom sediment gamma dose rates by use of the "Flounder" on the Tennessee River are not justified with the data available.

Since bottom sediments are generally covered by water, the gamma dose rate to the gonads of an individual standing on the river bottom would be reduced by attenuation. An average attenuation coefficient for water was calculated by weighting both the fraction of a disintegration that leads to a photon of a given energy from a particular radionuclide and the fraction each radionuclide contributes to the total loading of the bottom sediments. The fraction of dose remaining is graphed as a function of the depth of water (Fig. 13). The estimated gamma dose rates after attenuation through 3 feet of water are listed in Tables 26 and 27.

Cumulative Aggregate Dose to Exposed Populations

The aggregate exposure dose of individuals or critical population groups that resulting from disposal of radioactive waste to the Clinch River can not be estimated precisely. The principal reasons for this is the lack of information on habits and characteristics of the potentially exposed groups. Data on location and age distribution of potentially exposed populations, amounts of important foodstuffs consumed, methods of food preparation, and principal recreational habits are needed to define the total exposure dose. Age differences in metabolic rates or processes of children or adults as they relate to the important radionuclides, differences in radionuclide removal from river water by suspended solids and by water treatment processes, and differences in the transfer of

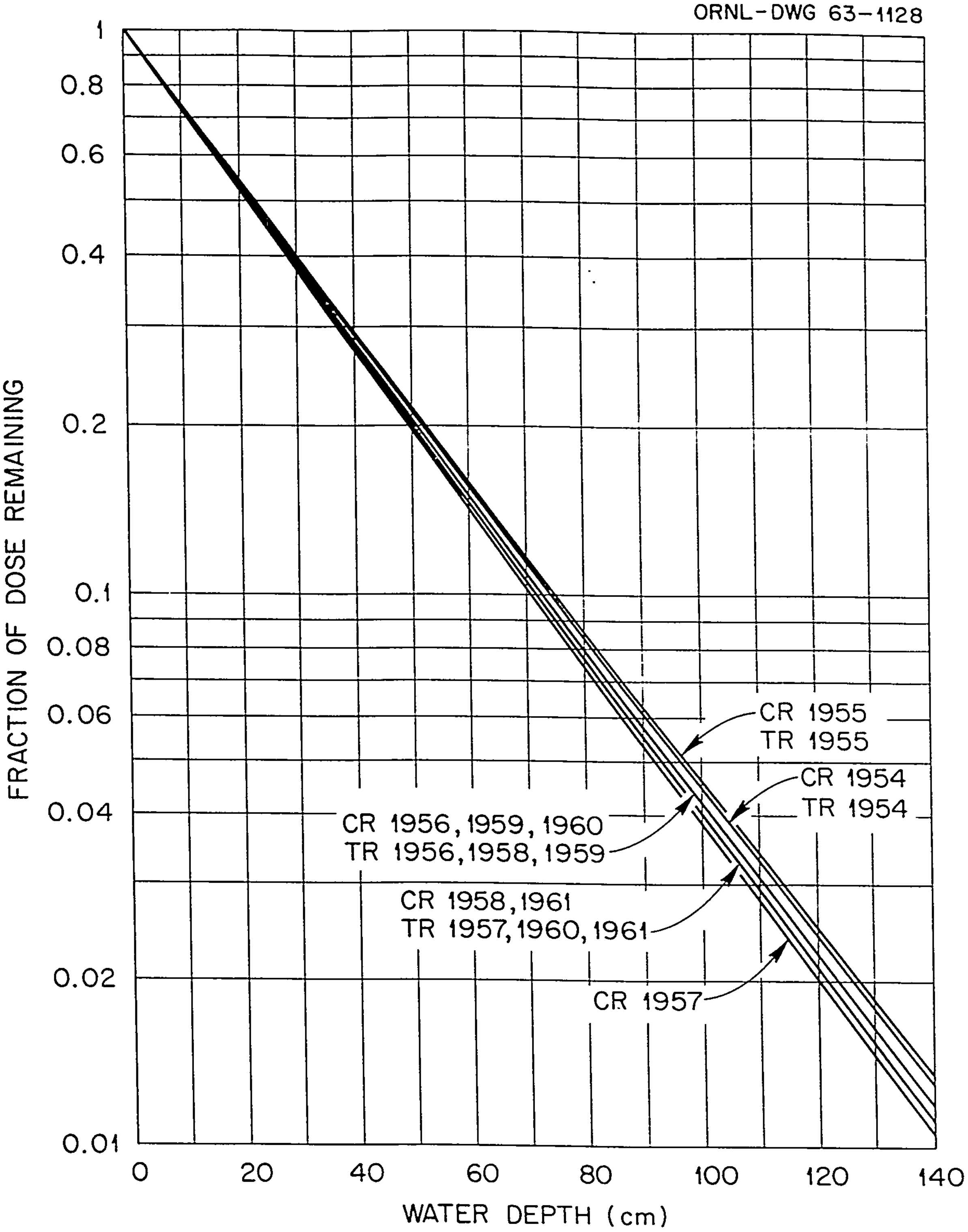


Figure 13. Attenuation of Bottom Sediment Dose in Clinch River and Tennessee River.

radionuclides from contaminated water to fish must also be considered. Although a single critical population group may be defined for a particular exposure pathway there is no reason to postulate the same critical population group for all exposure pathways.

By selecting reasonable values for periods of occupancy and dietary habits, an estimate can be made of the aggregate exposure dose (from 1944 to 1963) to the skeleton and total body of males working and residing in the Clinch-Tennessee River environment (Table 29). The fractions of allowable dose received by the thyroid and GI tract is smaller than that received by the total body and is not included. Since the Clinch River does not serve as a source of municipal water, children do not consume this water directly. Therefore, it is assumed that the youngest age group at the beginning of exposure is the 18-year old employed at the ORGDP. Only one-half of the daily fluid intake takes place on the job, and results in an estimated exposure dose of 1.4 rem and 0.11 rem to the skeleton and total body, respectively. The Tennessee River is used as a municipal water supply and, consequently, the 14-year old is the likely critical population group; the estimated dose from drinking this water is shown in Table 10. Dose from recreational use of the environment (listed in Table 29) is based on the following assumptions: an exposure time of 100 hours per year; an attenuation of bottom sediment radiation by three feet of water; the use of average concentrations of radionculides found in water and sediments to estimate dose for periods when data are lacking; and the adsorption of beta particles by the flesh of man thus limiting the exposure of the skeleton to gamma radiation. Only the feet of the swimmer could be totally exposed to the radiation from contaminated bottom sediments, but this would not exceed about 30 times the dose from recreational exposure given in Table 29. Occupational exposure from work within a water treatment plant is not significantly different from background radiation (see Table 22) and, therefore, is not considered in total exposure dose estimation.

The estimated dose from intake of contaminated fish, and the fraction of MPI attained by standard man from consuming 37 lbs per year of the flesh of contaminated bottom feeders is about equal to that from drinking contaminated water. However, the average fish consumption in the South is

TABLE 29

ESTIMATED CUMULATIVE DOSE RECEIVED BY CRITICAL ORGANS OF MALES FROM USE OF CLINCH RIVER AND TENNESSEE RIVER[a]

(rem)

Critical Pathway	Clinch River		Tennessee River	
	Skeleton	Total Body	Skeleton	Total Body
Drinking Water	1.4	0.11	0.38	0.030
Recreation	0.018	0.019	0.003	0.003
Fish	1.8	0.14	0.070	0.0057
Total	3.2	0.27	0.45	0.039
Maximum Permissible Dose[b]	60	10	20	1.0

[a]Aggregate exposure for the period 1944 to 1963.

[b]As recommended by ICRP (see references 4 and 8), the annual dose rates for continuous occupational exposure are reduced to 1/10 and applied to the Clinch River and are reduced to 1/30 for bone as critical organ and to 1/100 for total body as critical organ and applied to the Tennessee River.

24 lbs per year.[58] As a likely approximation, it is assumed that the total dose from eating Clinch River fish is 24/37 of the dose due to drinking Clinch River water and amounts to 1.8 rem and 0.14 rem to the skeleton and total body, respectively. It is further assumed that bottom feeders taken from the Tennessee River are diluted with other East Tennessee fish, and result in a total dose of 0.070 rem to the skeleton and 0.0057 rem to the total body. Thus, the estimated total dose in the skeleton of the 18-year old utilizing the Clinch River is 3.2 rem. The estimated dose to the skeleton of the 14-year old residing along the Tennessee River is 0.45 rem. In both cases the dose estimate is less than one-tenth of the maximum permissible dose. These estimated doses are believed to be high as a result of the conservative assumptions made in their estimation.

POTENTIAL EXPOSURES FROM CROP IRRIGATION

Irrigation of a variety of crops has been practiced in Tennessee for at least 50 years.[37] A survey conducted in 1958 by the Tennessee Division of Water Resources indicated that 1021 irrigation units were in operation at that time on about 0.5% of the crop lands; 20% were used for irrigating truck crops and 30% for irrigating feed crops (corn, silage, and hay). Ground water is the principal source of irrigation water west of the Tennessee River, and surface water is predominantly used in East Tennessee. More than 15 inches of water has been applied to truck crops during the growing season.

At present there is no crop irrigation along the Clinch River.[38] Therefore, an analysis of the possible consequences of transfer of fission products from contaminated river water to foods by crop irrigation is an hypothetical exercise. However, safety analyses are expected to point out future problem areas as well as assess the safety of current practice. Thus, the justification for such an exercise lies in uncovering any long-term problems that may be associated with usage of this natural resource.

Direct measurements of soil or crop loading with fission products due to irrigation practice, as distinguished from fallout and rainout are not available. It is necessary, therefore, to estimate the exposure dose that man may receive from intakes by this path on the basis of assumptions on soil loading, transfer coefficients from soil to crop, foliar contamination, and dietary habits of man.

Soil Load

Ion Exchange Reactions and Parameters

When water containing fission products is passed through a soil, the radioactive cations are removed from solution by ion exchange and their movement is restricted. Stable ions also exchange with those previously on the soil.

In the case of a divalent-monovalent ion system, it was assumed that all divalent ions behave similarly. The monovalent ions compete with the divalent ions for the exchange sites according to the expression, $2MR + D^{++} = DR_2 + 2M^+$, where D and M stand for divalent and monovalent notation.[39] The selectivity coefficient of divalent to monovalent ions is represented by[40]

$$K_M^D \ (g/ml) = \left(\frac{q_D}{C_D}\right) \left(\frac{C_M}{q_M}\right)^2 \tag{20}$$

where

K_M^D is the selectivity coefficient of D with respect to M, q_D and q_M are the partial exchange capacities for D and M(meq/g) and C_D and C_M are the equilibrium concentration of D and M in solution (meq/ml).

From equation 20 and taking the total exchange capacity $Q = 0.15 \frac{meq}{g}$ $(Q = q_M + q_D)$, the selectivity coefficient $K_M^D = 30$ g/ml,[41] and the concentration of stable ions in Clinch River and Tennessee River water $C_D = .00164 \frac{meq}{ml}$ (calcium plus magnesium) and $C_M = .000142 \frac{Meq}{ml}$ (sodium plus potassium), the partial divalent cation capacity of the soil is calculated to be $0.1497 \frac{meq}{g}$. Even if the selectivity coefficient were as low as unity, the divalent cations would occupy over 99% of the exchange sites because of valence effects.

The selectivity coefficient of strontium to calcium on the exchanger can be expressed by

$$K_{Ca}^{Sr} = \left(\frac{q_{Sr}}{C_{Sr}}\right) \quad \left(\frac{C_D}{q_D}\right) = K_{d_{Sr}} \left(\frac{C_D}{q_D}\right) \tag{21}$$

where

$K_{d_{Sr}}$ = (distribution coefficient) is the ratio of the concentration of strontium sorbed per unit weight of exchanger to the concentration of unsorbed strontium per unit volume of solution, at equilibrium

By the use of the distribution coefficient, an estimate can be made of the soil loading of a particular radionuclide at equilibrium. From equation 21, assuming the strontium will not affect the partial exchange capacity $q_D = 0.1497$, and taking $K_{Ca}^{Sr} = 1.3$,[40] and the concentration of stable calcium plus magnesium $C_D = 0.00164\ \frac{meq}{ml}$, the distribution coefficient for strontium is calculated to be 120 ml/g. From measurements, an average $K_{d_{Sr}}$ of 110 $\frac{ml}{g}$ is reported for Clinch River sediments.[43]

By similar considerations, the selectivity coefficients of cesium to sodium on the exchanger can be expressed as

$$K_{Na}^{Cs} = \left(\frac{q_{Cs}}{C_{Cs}}\right) \left(\frac{C_M}{q_M}\right) = K_{d_{Cs}} \left(\frac{C_M}{q_M}\right) \tag{22}$$

where

$K_{d_{Cs}}$ = (distribution coefficient) the ratio of the concentration of cesium sorbed per unit weight of exchanger to the concentration of unsorbed cesium per unit volume of solution, at equilibrium.

For the case of cesium exchange by local Conasauga shale, the estimation of soil loading is more involved. There are small quantities of exchange sites (fixation sites) highly selective for the heavy alkali metal cations (K^+ through Cs^+), and the selectivity for cesium compared to the stable ions of the system varies with the relative concentrations. Consequently, the use of equation 20 to estimate the partial monovalent loading would be misleading, since it would indicate a low value for cesium loading when substituted in equation 22.

Study of cesium exchange by Conasauga shale indicates that the number of exchange sites highly selective for cesium amounts to about 0.013 $\frac{meq}{g}$.[44] For the total exchange complex it is found that for $\frac{C_{Cs}}{C_{Na}} = 10^{-5}$ (typical of Clinch and Tennessee River water), $K_{Na}^{Cs} = 2000$. Because the majority of the exchange sites have little affinity for cesium compared to sodium, practically all of the cesium would be held at the fixation sites; the cesium to sodium selectivity coefficient of the fixation sites is estimated to be approximately $\frac{0.15}{0.013} \times 2000$ or 2.3×10^4. No valence effect is observed for the fixation sites; however, potassium is found to be approximately 10 times and calcium 9 times as effective as sodium in inhibiting the sorption of cesium. Magnesium is assumed to be as effective as calcium in restricting cesium sorption. The effective concentration of competing cations is taken as $C_M = C_{Na} + 10\ C_K + 9\ C_{Ca} + 9\ C_{Mg} = 0.015\ \frac{meq.}{ml}$. Since $q_{Cs} >> q_M$, q_M is assumed to be equal to the concentration of fixation sites.

From equation 22, when $K_{Na}^{Cs} = 2.3 \times 10^4$, $q_M = 0.013\ \frac{meq}{g}$, and $C_M = 0.015\ \frac{meq}{ml}$, the distribution coefficient is calculated to be $2.1 \times 10^4\ \frac{ml}{g}$. An average $K_{d_{Cs}}$ for Clinch River sediments is reported to be $2.9 \times 10^4\ \frac{ml}{g}$.[32]

Estimation of Soil Loading

The fission product loading of the soil is estimated by assuming that the soil will continue to remove all applied exchangeable cations until saturated to the equilibrium value. The volume of irrigation water required to attain equilibrium may be calculated by use of the distribution coefficients and the mass of soil available. Assuming a soil depth of 6 2/3 inches and a soil density (dry weight) of 1.32 g/cm^3, the estimated soil mass per square meter is 2.24×10^5 g. The depth of irrigation water required to attain equilibrium for ^{90}Sr is given by:

$$120\ \frac{ml}{g} \times 2.24 \times 10^5\ \frac{g}{2} \times 3.28\ \frac{ft}{m} \times 10^{-6}\ \frac{m^3}{cm^3} = 88\ ft$$

Similarly, for ^{137}Cs, 16,000 feet of water would be required to reach equilibrium. Water applied after the soil reaches its equilibrium load is assumed to have little additional effect on soil loading.

In an operating irrigation system, the accumulation of any particular fission product in the soil over a differential time element, dt, is assumed to be expressed by the equation:

$$\frac{dN(t)}{dt} = R - \lambda N(t) - aN(t) - \beta N(t) \tag{23}$$

where

$N(t)$ = quantity of radionuclide $\left(\frac{\mu c}{m^2}\right)$,

R = rate of application of the fission product $\left(\frac{\mu c}{yr\text{-}m^2}\right)$,

λ = decay constant (yr^{-1}) of the fission product,

a = fractional loss per year of fission product to the crop (yr^{-1}),

β = fractional loss per year of fission product due to other causes such as soil erosion, leaching, etc (yr^{-1}).

The loss of ^{90}Sr and ^{137}Cs from the soil zone by erosion, leaching, surface runoff, and interflow, is assumed to be negligible. In reality, some loss by these machanisms is expected. Numerous accounts of the occurrence of ^{90}Sr and ^{137}Cs in soils indicate only a slow movement of these radionuclides through the soil by leaching.[45-50] Loss of ^{90}Sr in fallout due to erosion and runoff is related to the soil cover and the land slope on plots growing agricultural crops. Investigation of plots in Wisconsin and Georgia indicate losses by erosion and runoff ranging from 0.4% to 4.0%.[51] Studies are currently in progress at ORNL to define the loss of radionuclides by erosion and runoff from local soil plots. The solution of equation 23 when

$N(t) = 0$ at $t = 0$, and $\beta = 0$ is:

$$N(t) = \frac{R}{\lambda + a} \left(1 - e^{-(\lambda + a)\, t}\right) \tag{24}$$

The rate of application of fission products to the agricultural plot is a function of the quantity of irrigation water used and the concentration of fission products in the water. Tables 30 and 31 list the build-up of ^{90}Sr and ^{137}Cs in soil resulting from an assumed rate of application of 2 ft of Clinch River water and Tennessee River water per year. The concentration of ^{90}Sr in the water is assumed to be constant, either at the level that occurred in 1951 or at the level that occurred in 1954. Similarly, ^{137}Cs concentrations are assumed constant at the level of 1953 or at the level of 1956. Separate land areas are assumed to support the growth of grain, leafy vegetables, potatoes, or pasture grass. Values chosen for the fractional loss (a) of ^{90}Sr and ^{137}Cs to the various crops are discussed below. Due to radioactive decay and to the fractional loss to the crop, ^{137}Cs essentially reaches equilibrium in the soil system after 100 years of irrigation. An external dose rate of less than 0.1 mrad/day is associated with the contaminated soil at equilibrium.

Transfer of Radionuclides to Man through Soil

Plant growth requires that ions from the soil be removed continuously and relocated within the plant. This dynamic system allows fission products in the soil to be transferred to the plant. Values reported for ^{90}Sr and ^{137}Cs transferred from soil to crop vary by a factor of about 10.[52-57] Many of the transfer coefficients result from experimental studies that require an extrapolation to field conditions. Selection of transfer coefficients for this study consider the exchangeable calcium, the cation exchange capacity, the pH, and the exchangeable hydrogen of local soils. An estimated plant load ($\frac{\mu c}{kg}$ dry weight) is based on soil to crop transfer of 0.01% of the ^{137}Cs (all crops), 0.005% of the ^{90}Sr to wheat grain, and 1% of the ^{90}Sr to other crops, and an edible crop yield of 0.14 kg/m^2 dry weight for wheat grain (typical for East Tennessee) and one kg/m^2 for all other crops.

Estimated Intake of ^{90}Sr and ^{137}Cs

The daily intake of ^{90}Sr and ^{137}Cs is estimated by assuming that all produce for the year comes from the same irrigated soil, and that the dietary habits of the individual include an average daily intake of 0.24 kg of grain, 0.26 kg of leafy vegetable, and 0.1 kg of potatoes.[58] Most of the wheat grain is in the form of white flour; therefore, only 25% of the ^{90}Sr in grain is expected to reach the flour and be consumed by man.[59]

By assuming that the maximum permissible intake (MPI) of a radionuclide ($\frac{\mu c}{day}$) is simply the product of the $(MPC)_w$ and the volume of water consumed by the standard man (2200 ml/day), the fraction of MPI that may be attained by consuming contaminated produce is calculated (Table 32 and 33). Inherent in the calculation is the assumption that rainfall will not affect the soil loading and that the fission products will be uniformly distributed within the soil by land cultivation procedures.

TABLE 30

THE ESTIMATED CUMULATION OF ^{90}SR IN IRRIGATED SOIL
(10^{-2} $\mu c/m^2$)

Years of Irrigation	1951 Type of Crop: Grain	1951 Type of Crop: Leafy Vegetable or Grass	1951 Type of Crop: Potato	1954 Type of Crop: Grain	1954 Type of Crop: Leafy Vegetable or Grass	1954 Type of Crop: Potato
CLINCH RIVER MI 14.5						
1	0.30	0.30	0.31	2.9	2.9	3.0
2	0.60	0.58	0.62	4.9	5.7	6.1
5	1.4	1.3	1.5	14	13	14
11	2.8	2.3	2.9	28	22	28
30	4.7	3.4	5.9	56	34	57
44	6.9	3.6	7.1	67	36	69
TENNESSEE RIVER MI 465.5						
1	0.050	0.050	0.052	0.33	0.33	0.35
2	0.10	0.098	0.11	0.67	0.65	0.70
5	0.24	0.22	0.24	1.6	1.4	1.6
11	0.48	0.38	0.49	3.2	2.5	3.2
30	0.96	0.58	0.99	6.4	3.9	6.6
44	1.2	0.61	1.2	7.7	4.1	7.9

TABLE 31

ESTIMATED CUMULATION OF ^{137}CS IN IRRIGATED SOIL

(10^{-2} $\mu c/m^2$)

Years of Irrigation	1953 Type of Crop: Grain	1953 Type of Crop: Leafy Vegetables, Potatoes, or Grass	1956 Type of Crop: Grain	1956 Type of Crop: Leafy Vegetables, Potatoes, or Grass
CLINCH RIVER MI 14.5				
1	0.096	0.095	2.2	2.2
5	0.42	0.37	9.8	8.7
10	0.71	0.57	17	13
30	1.2	0.79	28	18
50	1.3	0.81	31	19
100	1.4	0.81	32	19
TENNESSEE RIVER MI 465.5				
1	0.015	0.015	0.36	0.36
5	0.065	0.058	1.6	1.4
10	0.11	0.090	2.7	2.2
30	0.19	0.12	4.6	3.0
50	0.21	0.13	5.0	3.1
100	0.21	0.13	5.2	3.1

TABLE 32

ESTIMATED FRACTION OF ^{90}SR MPI THAT MAN MAY ATTAIN BY TRANSFER FROM SOIL CONTAMINATED WITH IRRIGATION WATER[a]
(10^{-1} MPI)

Years of Irrigation	1951 Grain	1951 Leafy Vegetables	1951 Potato	1954 Grain	1954 Leafy Vegetables	1954 Potato
CLINCH RIVER MI 14.5						
1	0.0007	0.086	0.035	0.0070	0.85	0.34
2	0.0015	0.017	0.072	0.014	1.7	0.70
5	0.0035	0.39	0.17	0.034	3.7	1.6
11	0.0069	0.65	0.33	0.067	6.4	3.2
30	0.014	1.0	0.67	0.14	9.8	6.6
44	0.017	1.1	0.81	0.16	10	8.0
TENNESSEE RIVER MI 465.5						
1	0.0004	0.049	0.020	0.0027	0.32	0.13
2	0.0008	0.095	0.040	0.0054	0.63	0.27
5	0.0020	0.21	0.094	0.013	1.4	0.62
11	0.0042	0.37	0.19	0.026	2.4	1.2
30	0.0078	0.56	0.38	0.052	3.7	2.5
44	0.0094	0.59	0.44	0.062	4.0	3.0

[a]Considering bone as the critical organ.

TABLE 33

ESTIMATED FRACTION OF ^{137}Cs MPI THAT MAN MAY ATTAIN BY TRANSFER FROM SOIL CONTAMINATED WITH IRRIGATION WATER (10^{-4}MPI)[a]

Years of Irrigation	1953 Grain	1953 Leafy Vegetables or Potato	1956 Grain	1956 Leafy Vegetables Or Potato
		CLINCH RIVER MI 14.5		
1	0.0013	0.0077	0.031	0.18
5	0.0051	0.030	0.13	0.71
10	0.0096	0.047	0.23	1.1
30	0.017	0.064	0.39	1.4
50	0.018	0.066	0.42	1.5
100	0.019	0.066	0.44	1.5
		TENNESSEE RIVER MI 465.5		
1	0.0020	0.012	0.049	0.29
5	0.0088	0.047	0.22	1.2
10	0.015	0.073	0.37	1.8
30	0.026	0.099	0.63	2.4
50	0.028	0.10	0.69	2.5
100	0.029	0.10	0.70	2.5

[a]Considering total body as the critical organ.

After 44 years of irrigation with waters containing a constant concentration of ^{90}Sr an equilibrium is established and an increase in ^{90}Sr intake would not be expected. At the estimated rate of consumption of both grain and leafy crops, the hypothetical intake of ^{90}Sr at equilibrium using Clinch River water for irrigation may range from 0.19 to 1.8 times MPI; similarly, the hypothetical intake of ^{90}Sr at equilibrium using Tennessee River water may range from 0.10 to 0.71 times MPI. At the current levels of ^{137}Cs in Clinch River and Tennessee River water, no apparent problems will be encountered.

Experimental results from a number of studies of radionuclide uptake by plants are summarized by the Stanford Research Institute.[60] Transfer of radionuclides from soil to crop is expressed as a soil uptake contamination factor, A_{su} or the ratio of atoms per gram of dry plant to the atoms per gram of soil. By considering the characteristics of East Tennessee soils, average values of $A_{su}(^{90}Sr)$ are calculated for various crops as follows: grain, 0.05; potatoes, 0.26 dark green and deep yellow vegetables (spinach, broccoli, carrots, etc.), 3.3; other green vegetables (beans, peas, lettuce, etc.), 4.6; and other vegetables (beets, radishes, etc.), 3.6. The daily intake of ^{90}Sr is estimated from the dietary habits in the South and the soil loading at equilibrium (Table 30, Clinch River, 1954).[58] Based on the estimated daily intake of ^{90}Sr, a standard man is calculated to attain about two times the MPI due to soil to crop transfer. Another comparison of calculated values of ^{90}Sr content in edible foods is afforded by the Federal Radiation Council.[61] They predict an average accumulation of 0.044 μc of ^{90}Sr per square meter from fallout at the end of 1963, and 250 pc of ^{90}Sr per kilogram in harvested wheat. Using the assumptions of soil to grain transfer and productivity previously listed, the estimated ^{90}Sr in grain is 15 pc per kilogram. Thus about 5% of the ^{90}Sr expected in wheat grain may come from the soil and about 95% from absorption through above ground parts of the plant. Menzel reports similar values for foliar retention of ^{90}Sr by wheat grain.[62] The importance of contaminated irrigation water as a critical pathway receives support from experimental field studies reported by Michon.[63] Results indicate the average ^{90}Sr content in one kilogram of the crops studied is equivalent to the ^{90}Sr in at least 9.5 liters of the irrigation water.

Transfer of Radionuclides by Foliar Contamination

To a large extent crop irrigation is accomplished by spray techniques. Thus, foliar contamination of above ground crops is another avenue by which fission products in irrigation water may reach man. Studies of aerial contamination of plants have been related principally to absorption of fallout radionuclides; therefore, uncertainties exist in applying data from such studies to crop contamination by irrigation. The amount of radionuclide accumulated in edible parts of a plant depends on the stage of growth of the plant at the time of spraying, and the rate of translocation and rate of accumulation of the radionuclide.[64] Intermittant rainfall is known to remove a fraction of the radionuclide previously deposited on plants. The values of percent retention by the edible part of plants vary considerably between different crops. Grain is reported to contain from 0.2% to 2% of the ^{90}Sr, and apparently depends on the season and time of contamination.[62,65-67] The final content of ^{137}Cs in wheat grain ranges from 1% to 5%. Potatoes contain significantly smaller amounts of ^{90}Sr than other vegetable crops; the final content in tubers ranges from 0.01% to 0.04%. Cesium-137 retention by tubers averages about 9%.[68] Estimates of retention by leafy vegetables are based on values reported for pasture grass and the wheat plant. Retention of ^{90}Sr varies between 2.5% and 5%, and ^{137}Cs retention is about 10%.[68,69]

Values selected for foliar retention of ^{90}Sr and ^{137}Cs for this analysis are based on the above information and are listed in Table 34. By irrigating the various crops with two feet per year of Clinch River and Tennessee River water that contain concentrations of ^{90}Sr and ^{137}Cs previously listed, the fraction of MPI that might be attained due to foliar contamination is calculated (Table 34). Foliar contamination with ^{90}Sr has a greater influence on leafy crops than grain or potato crops. At the levels of ^{137}Cs encountered in the rivers during 1953 and 1956, a smaller but perceptable amount of ^{137}Cs may enter man's diet due to foliar contamination as contrasted to soil to plant contamination.

Transfer of Radionuclides to Man by Milk

One final possibility of radionuclide transfer to man by contaminated

TABLE 34

TRANSFER OF ^{90}SR AND ^{137}CS TO MAN BY FOLIAR CONTAMINATION FROM IRRIGATION WATER

Source	Year	Percent Retention[a]			Plant Load[b] (10^{-4} μc/kg)			Fraction of MPI[c]		
		Grain	Leafy Vegetables	Potato	Grain	Leafy Vegetables	Potato	Grain	Leafy Vegetables	Potato
STRONTIUM-90										
CRM 14.5	1951	1.0	5.0	0.03	2.2	1.6	0.012	0.015	0.045	0.00014
CRM 14.5	1954	1.0	5.0	0.03	22	15	0.092	0.15	0.45	0.0011
TRM 465.5	1951	1.0	5.0	0.03	.38	0.27	0.0016	0.0087	0.033	0.00006
TRM 465.5	1954	1.0	5.0	0.03	2.5	1.8	0.011	0.058	0.17	0.0004
CESIUM-137										
CRM 14.5	1953	5.0	10	10	3.6	1.0	1.0	0.0020	0.00059	0.00022
CRM 14.5	1956	5.0	10	10	84	23	23	0.046	0.014	0.005
TRM 465.5	1953	5.0	10	10	.56	0.16	0.16	0.0031	0.0009	0.0004
TRM 465.5	1956	5.0	10	10	14	3.8	3.8	0.074	0.022	0.009

[a] Contents of edible plant as % of radionuclide applied per unit of land area.

[b] kg of dry weight

[c] Assuming a daily intake of man of 0.24 kg of grain, 0.26 kg of leafy vegetables, and 0.10 kg of potatoes.

irrigation water is considered; that is, the transfer of the radionuclides into the milk of cows allowed to graze on pasture land irrigated with river water. Information assembled by the United Nations Scientific Committee on the Effects of Atomic Radiation indicates that 0.08% of the ^{90}Sr and 1.3% of the ^{137}Cs ingested daily by dairy cattle is transferred to each liter of milk.[70] The intake of these radionuclides by the cow is based on an average daily consumption of 10.9 kg of pasture grass.[71]

Using the previously calculated values of leafy crop loading due to soil to crop transfer and direct foliar contamination, and assuming that one liter per day of milk is consumed, the fraction of MPI that may be obtained by drinking milk is estimated (Table 35). The hypothetical intake of ^{90}Sr at equilibrium using Clinch River water and Tennessee River water for irrigation may result in an MPI ranging from 0.0052 to 0.051 MPI and 0.0029 to 0.019 MPI, respectively. At the levels of ^{137}Cs in the irrigation water, no apparent problem is encountered. Since foliar retention is the principal mechanism of ^{137}Cs transfer to grass, there is little change in loading from year to year. At equilibrium, the fraction of MPI (total body as critical organ) attained is: Clinch River, 3.2×10^{-4} (1953) and 7.6×10^{-3} (1956); and Tennessee River, 5.1×10^{-4} (1953) and 1.2×10^{-2} (1956).

Cumulative Transfer of Radionuclides to Man by Crop Irrigation

Although independent consideration was given to the several vectors of contaminating man's diet by irrigating water, these vectors are additive. Hypothetically, the cumulative contribution to the MPI (bone) of ^{90}Sr by irrigation water is shown in Figures 14 and 15. Similarly, the cumulative contribution to the MPI (total body) of ^{137}Cs by irrigation water is shown in Figure 16. Calculations indicate that soil to crop transfer of ^{90}Sr may be of greatest long-term importance in contributing ^{90}Sr to man's diet from contaminated irrigation water. Foliar and milk vectors may be only of secondary importance. After equilibrium is attained in the soil, standard man might ingest 20 times as much ^{90}Sr by consuming produce from the land irrigated with contaminated water compared to consumption of the water. No apparent problem is indicated due to the estimated concentration of ^{137}Cs in Clinch River and Tennessee River

TABLE 35

ESTIMATED FRACTION OF ^{90}SR MPI THAT MAN MAY ATTAIN FROM MILK AFFECTED BY CROP IRRIGATION[a]

Years of Irrigation	CLINCH RIVER Mi. 14.5		TENNESSEE RIVER Mi. 465.5	
	1951	1954	1951	1954
1	0.0019	0.018	0.0010	0.0069
2	0.0021	0.021	0.0012	0.0080
5	0.0028	0.028	0.0016	0.011
11	0.0038	0.037	0.0021	0.014
30	0.0050	0.049	0.0028	0.019
44	0.0052	0.051	0.0029	0.019

[a]Assuming a daily intake by man of one liter of milk and considering bone as the critical organ.

irrigation water. However, due almost entirely to foliar contamination, as much as 30 times the ^{137}Cs might be ingested from contaminated crops compared to drinking water. It is not possible to determine the accuracy of these predictions with the information currently available. A number of assumptions were necessary in making the calculations, and differences in the values used for transfer parameters could significantly change the estimated intake of ^{90}Sr and ^{137}Cs. For example, the loss of radionuclides from irrigated plots by erosion and runoff may reduce the quantity of radionuclides available to the plants. A change in soil to crop transfer, in foliar retention, or in productivity of edible crops, could either increase or decrease the quantity of ^{90}Sr and ^{137}Cs present in man's diet. Differences in dietary habits and use of produce from uncontaminated plots would also influence the estimated internal exposure.

At the present time no problem exists of significant quantities of fission products entering man's diet due to irrigation practice. It seems unlikely that a problem will develop along the Clinch-Tennessee River system. Truck crops in this environment contribute little to the total quantity of produce and are grown only for a short period during the year. However, crop irrigation with contaminated water could take on greater importance in areas where climatic conditions are more conducive to year-around irrigation of large agricultural plots. Some use can be made of data provided by fallout studies, but there is need for data from experiments designed to elucidate radionuclide entry into man's diet from contaminated irrigation water. In view of the long-range interest in a power reactor program and the accompanying recycle of fuels, such studies should consider the transmutation products (resulting from neutron capture by irradiated fuels), as well as fission products.

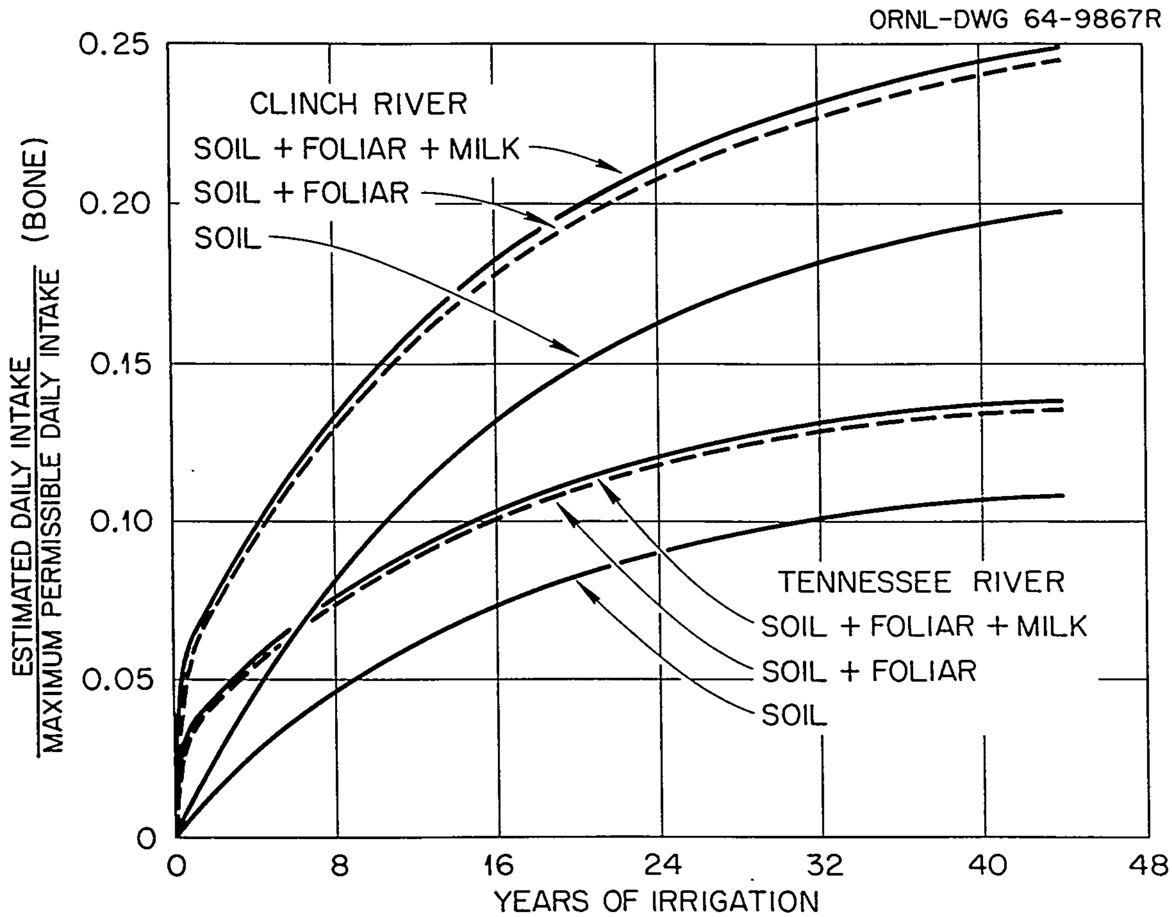


Fig. 14. Potential Contribution to MPI by Sr^{90} in Irrigation Water: 1951.

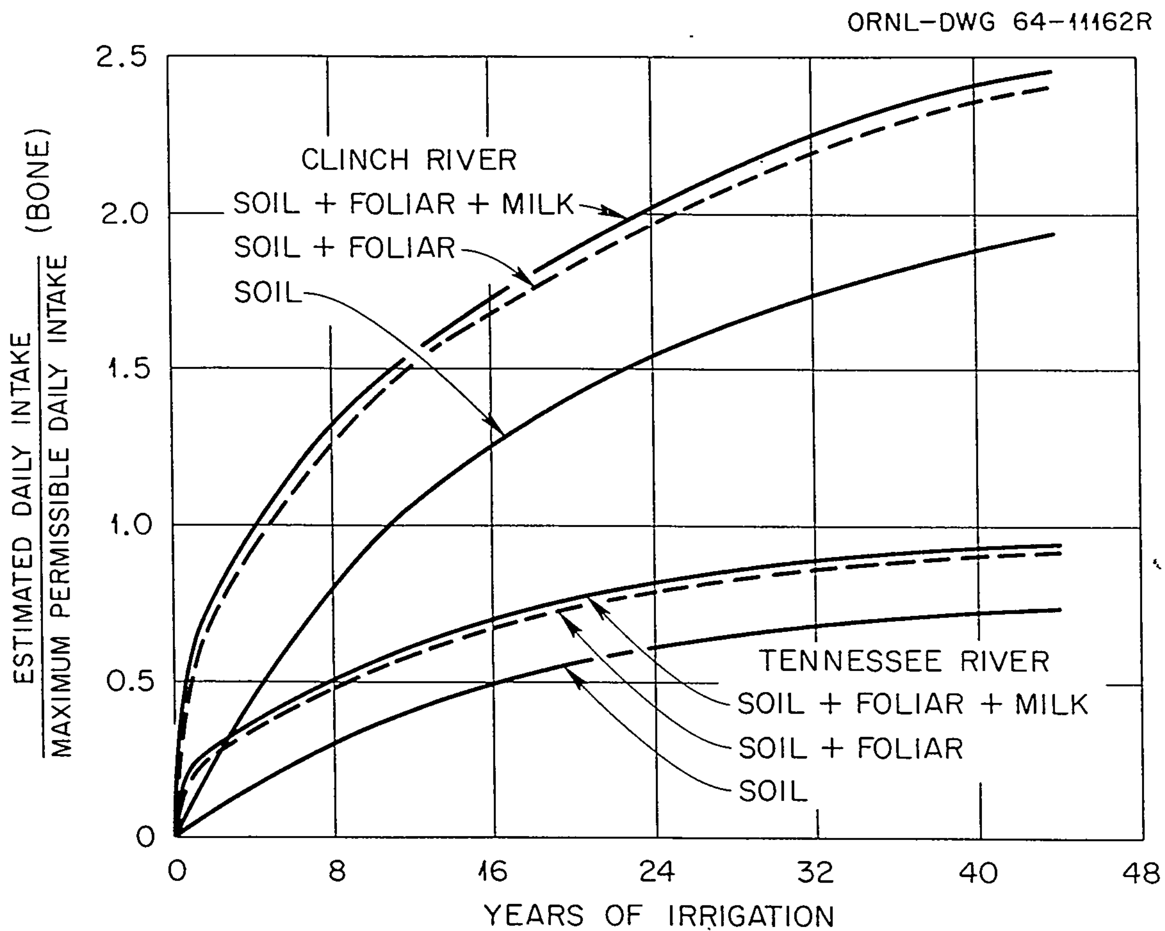


Fig. 15. Potential Contribution to MPI by Sr^{90} in Irrigation Water: 1954.

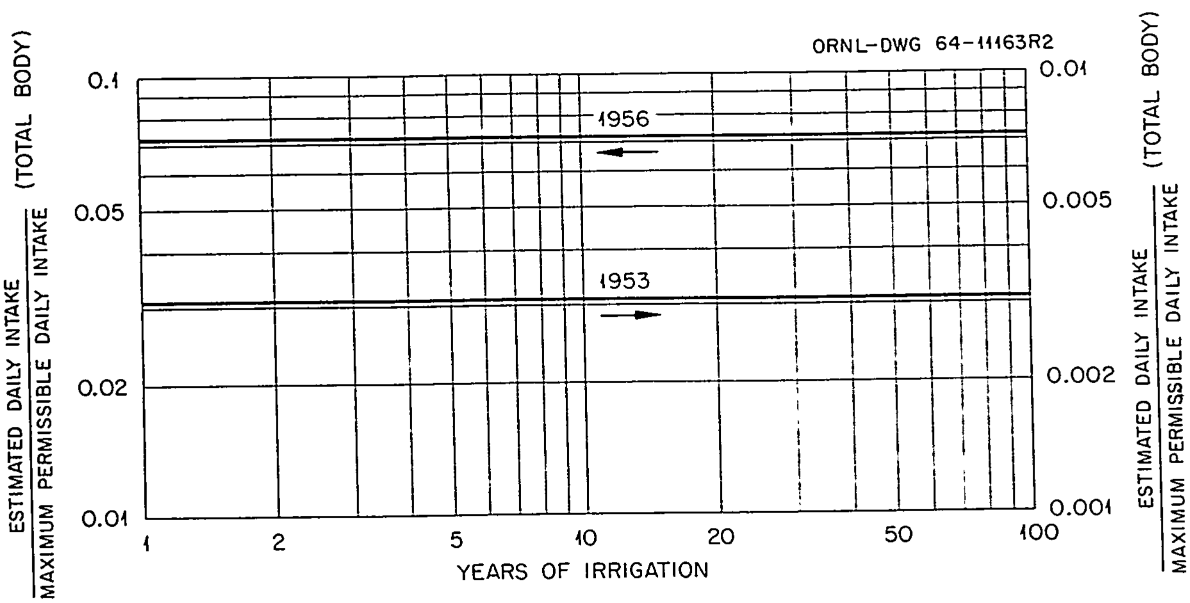


Fig. 16. Potential Contribution to MPI by Cs^{137} in Clinch River Irrigation Water.

CONCLUSIONS AND RECOMMENDATIONS

Disposal of radioactive wastes to the Clinch River has resulted in radiation exposures well below ICRP and FRC permissible limits. Of the critical pathways considered, external exposure from contaminated water and bottom sediments was of less importance as a potential source of radiation exposure than consumption of contaminated water and fish. However, if the practice of irrigation with river water develops, the long term effect of crop irrigation with contaminated water could become the most important avenue of exposure.

Internal dose estimations based solely on exposure of a standard man will underestimate the dose to critical population groups; that is, the most highly exposed group. By taking account of differences in rates of intake and masses of critical organs estimated doses exceed those of standard man by a factor of at least two. Such differences are in addition to those expected as a result of individual variability. Other improvements in dose estimates are possible but that will require better information on the habits and characteristics of population groups likely to be exposed. Such information includes the location and age distribution of potentially exposed populations, amounts of principal foodstuffs consumed, and their principal occupational and recreational habits. The type and rate of consumption of fish, potatoes, and leafy vegetables as a function of age would be extremely useful. In particular, additional information is necessary to decide if total fish (flesh and bone) are an important source of ^{90}Sr intake by man. Although the cooked flesh of fish is an established staple of man's diet, the consumption of total fish by East Tennessee fishermen is not confirmed.

Strontium-90 is the most important of the critical radionuclides in liquid wastes released to the Clinch River, contributing more than 99% of the skeleton and total body dose and 70% of the thyroid dose. Ruthenium-106, ^{137}Cs, and ^{60}Co contribute significantly to the dose received by the GI tract. As a consequence of ^{90}Sr releases, the skeleton of man drinking Clinch River water is the critical organ receiving about 5 times the total dose of the other organs considered. However, the total dose to the skeleton of the critical population group was considerably smaller (by a factor of about 20) than the allowable dose from contaminated drinking water. Improved waste management at ORNL has resulted in a decrease in ^{90}Sr released to the Clinch River. The more recent discharges to the river have been about equal to the contribution from nuclear test fallout.

An internal dose commitment is created for the future by the intake of radionuclides of long effective half life. Dose continues to be delivered to the critical organs following intake and depends on the effective half life of the radionuclide. Information on dose commitment may be useful if changes in population exposure limits are considered, if a new installation wishes to utilize the diluent capacity of a surface water, or if an accidental release of radioactive material requires corrective action. Methods developed in this report for estimating dose to man can be applied to the assessment of future radiation exposure.

Greatest emphasis of routine environmental monitoring should be related to current and critical pathways of exposure; for man, these are the consumption of water and fish. Periodic evaluation is needed to confirm the adequacy of the monitoring program and to reestablish the importance of critical nuclides and critical exposure pathways. Such review would be concerned not only with radionuclides of long physical half life, but also with those of short half life that may occasionally be released and otherwise overlooked by a routine program. The routine monitoring program should include comparison of gross beta analysis made on daily samples and on monthly composite samples, the difference in magnitude being indicative of the significance of the contribution of short lived radionuclides in the effluent. Although contaminated water and bottom sediments are a minor source of radiation exposure to man, direct measurements of radiation intensity are desirable initially to confirm dose-rate calculations and to occasionally reconfirm the source potential. It is also desirable to investigate current and possible future use of Clinch River and Tennessee River waters as sources of supplemental water for irrigation purposes. This information can be used to define the need for sampling soils or crops in the affected areas.

There is need for additional research on areas of uncertainty associated with radionuclide transfer to fish and to irrigated crops. Information such as the rate of transfer and quantity of ^{90}Sr and stable strontium in flesh and bone of important fish species, the influence of fish age and season of the year on transfer rates, and the transfer of ^{90}Sr from fish bone to fish flesh by cooking would be helpful to estimate the dose to man and to optimize a fish monitoring program. A potentially important source of ^{90}Sr entry in man's food chain can be eliminated by preventing fish in White Oak Creek or White Oak Lake from entering the Clinch River. Analysis of crop irrigation as a critical exposure pathway requires knowledge of fission product behavior in soils and plants. Of greatest importance is information applicable to the East Tennessee environs. This includes the accumulation of fission products in cultivated soils with time, the transfer of fission products from soil to plant, and the foliar retention of fission products by the plant.

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